Alfvénic Turbulence in High Speed Solar Wind Streams: Hints from Comet Plasma Turbulence

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Solar Wind at 1 AU

Plasma mainly protons and electrons (~4% Helium), $N_p \sim 3$ cm^{-3}

$T \sim 10^5$ K
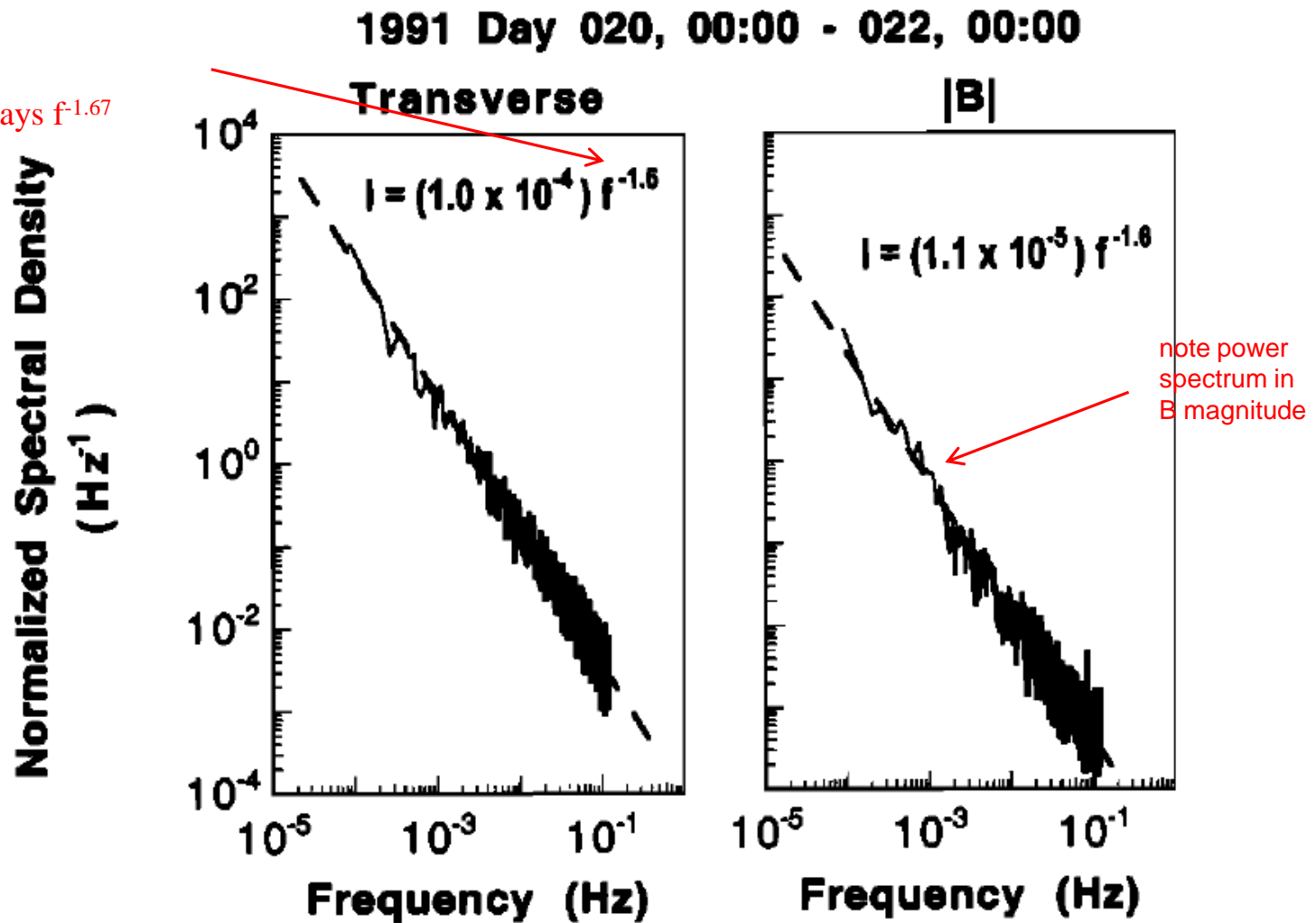
$B \sim 5$ nT

Beta ~ 1
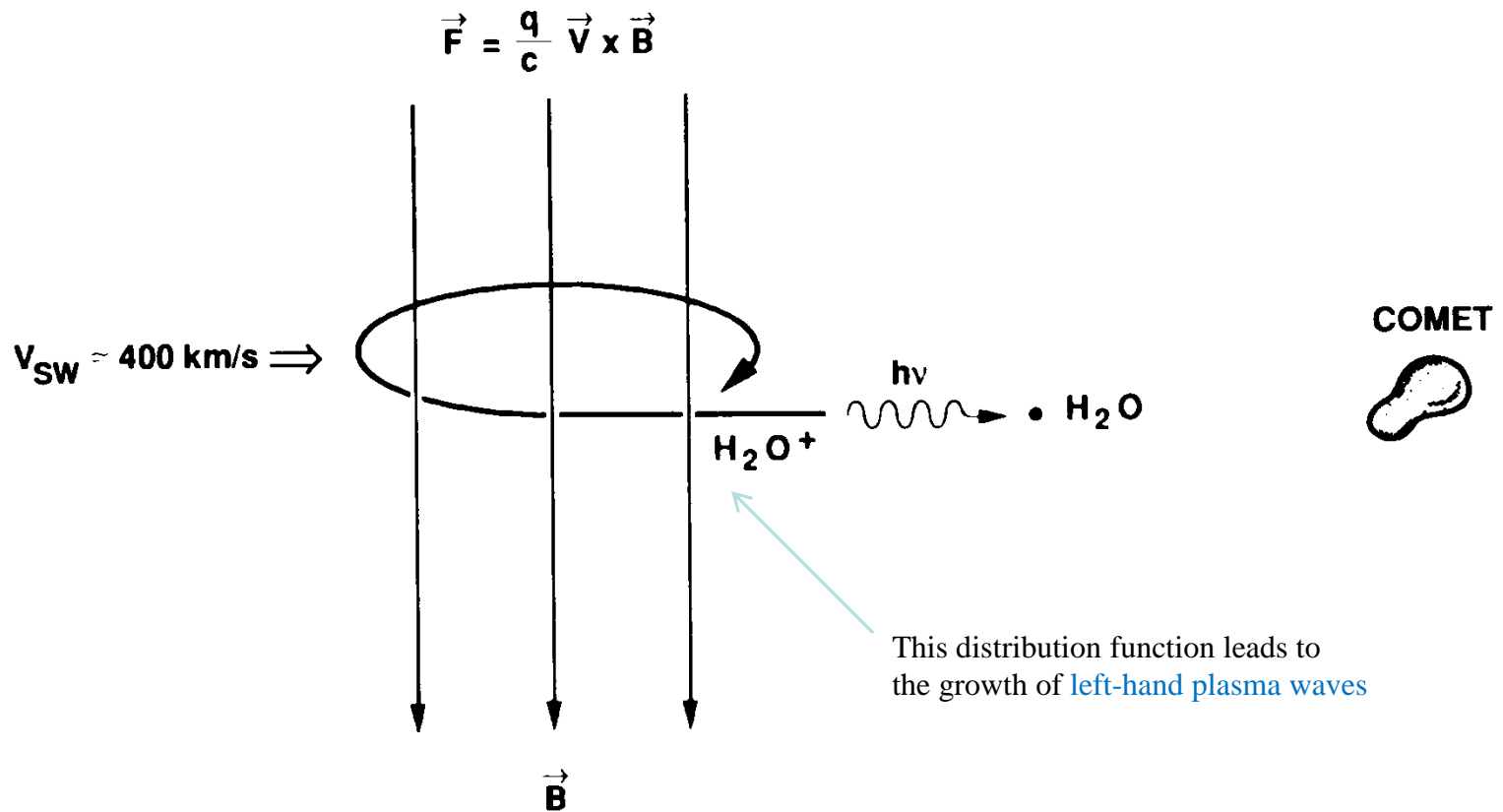
Coulomb collision scale ~0.3 to 3 AU (basically collisionless)

Interplanetary Turbulence in a Solar Wind High Speed Stream

Close to
but not always $f^{-1.67}$

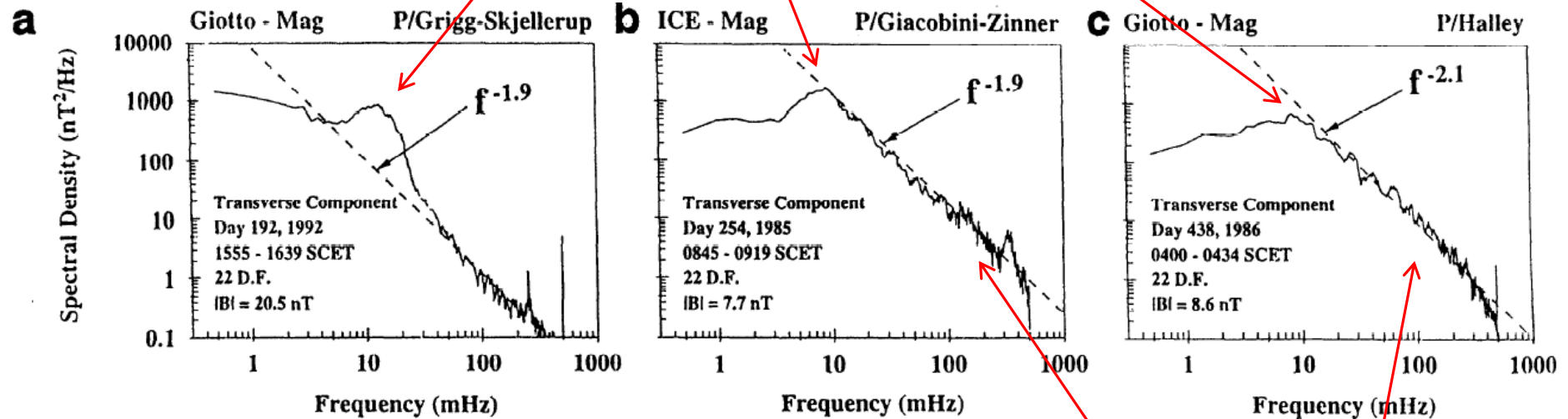### 1991 Day 020, 00:00 - 022, 00:00

Transverse

$I = (1.0 \times 10^{-4}) f^{-1.5}$

|B|

$I = (1.1 \times 10^{-5}) f^{-1.6}$

note power
spectrum in
B magnitude

Normalized Spectral Density (Hz^{-1})

Frequency (Hz)

Frequency (Hz)

JGR, 1996

Ion Pickup for Perpendicular Magnetic Fields: Mass Loading

$$\vec{F} = \frac{q}{c}\, \vec{V} \times \vec{B}$$

$V_{SW} \simeq 400 \text{ km/s} \Rightarrow$

H_2O^+

$h\nu$

$\bullet\ H_2O$

COMET

This distribution function leads to the growth of left-hand plasma waves

$\vec{B}$

Tsurutani, AGU monograph 1991

Power Spectra of Turbulence at 3 Different Comets

Pump wave at the H_2O group ion cyclotron frequency

a Giotto - Mag   P/Grigg-Skjellerup

Spectral Density (nT^2/Hz)

$f^{-1.9}$

Transverse Component
Day 192, 1992
1555 - 1639 SCET
22 D.F.
|B| = 20.5 nT

Frequency (mHz)

b ICE - Mag   P/Giacobini-Zinner

$f^{-1.9}$

Transverse Component
Day 254, 1985
0845 - 0919 SCET
22 D.F.
|B| = 7.7 nT

Frequency (mHz)

c Giotto - Mag   P/Halley

$f^{-2.1}$

Transverse Component
Day 438, 1986
0400 - 0434 SCET
22 D.F.
|B| = 8.6 nT

Frequency (mHz)

G-S field perp

G-Z field near par

All had ~f^{-2} power laws

Tsurutani, Glassmeier and Neubauer, GRL, 1995

The Waveforms at 3 Different Comets

a GIOTTO - Mag P/Grigg-Skjellerup — Day 192, 1451:20 - 1454:25 Universal Time (SCET) — G-S

b ICE - Mag P/Giacobini-Zinner — Day 254, 0912:30 - 0915:30 Universal Time (SCET) — G-Z
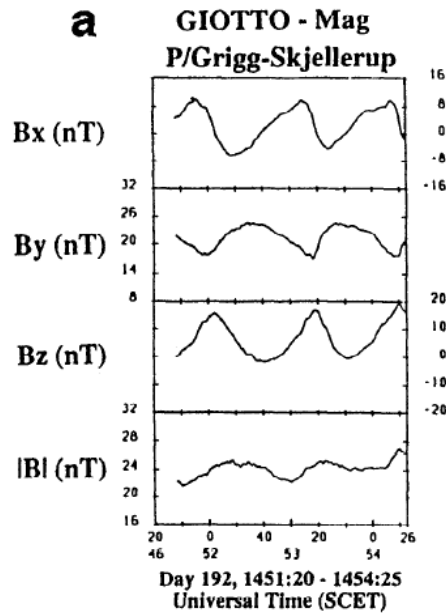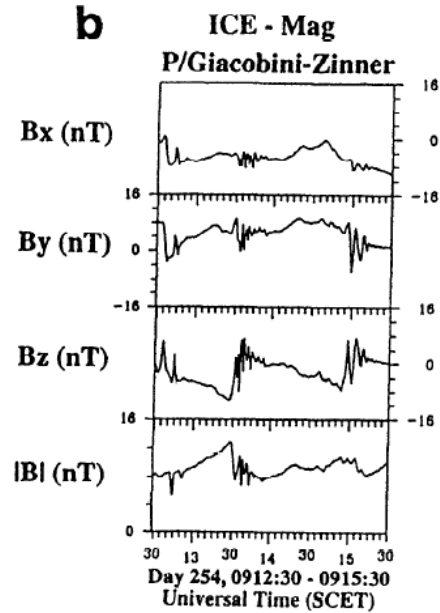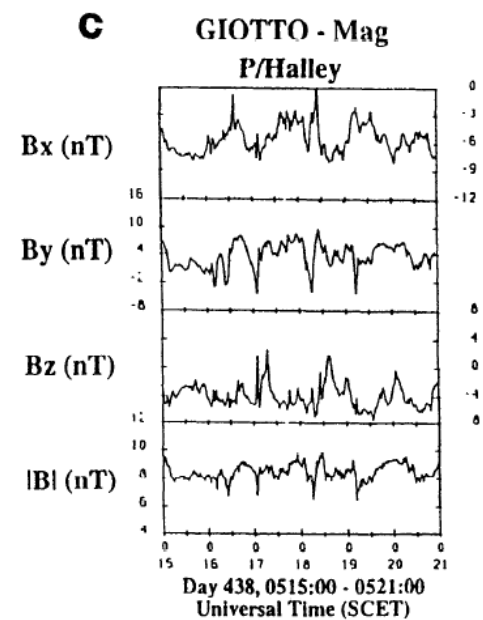
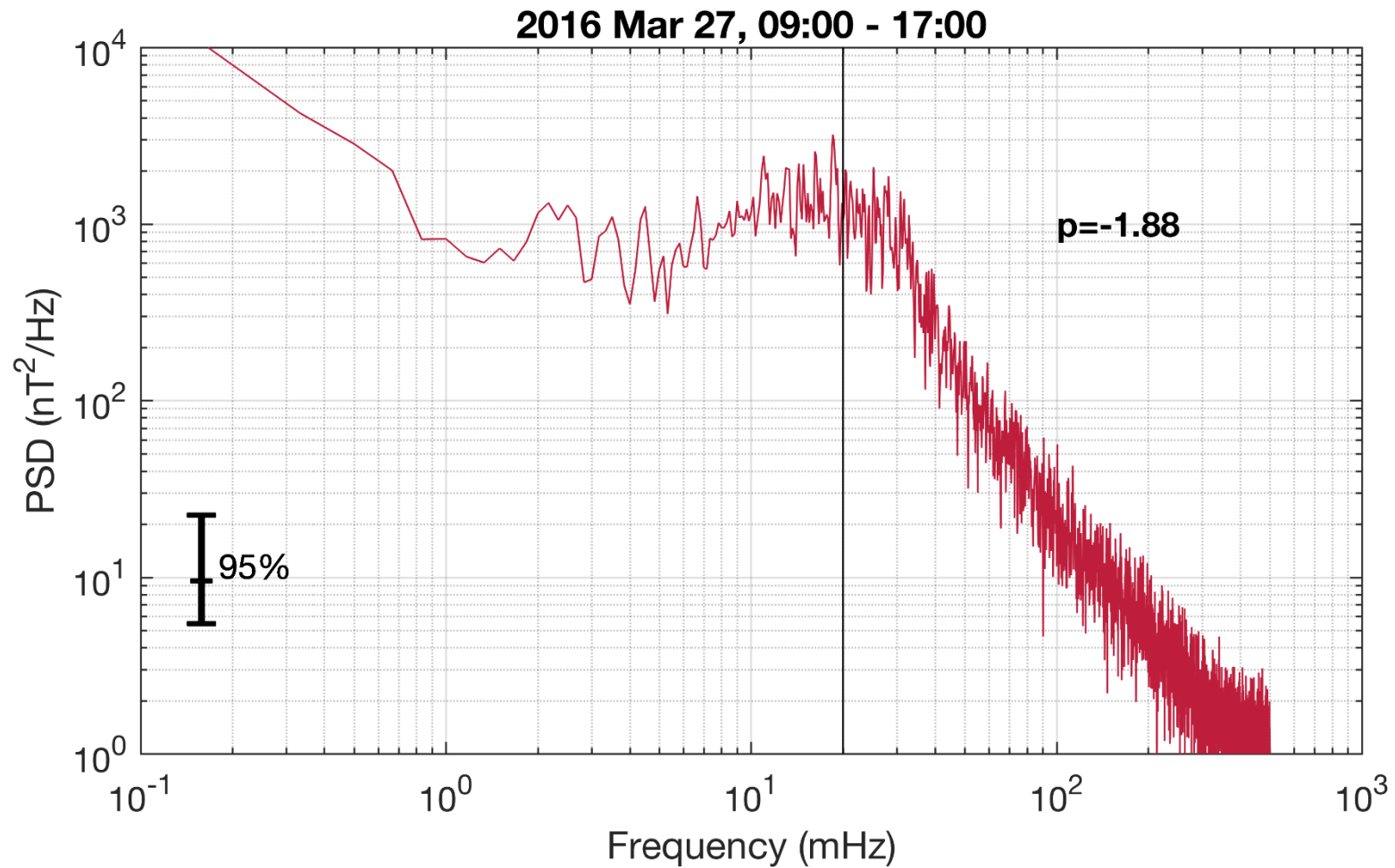**c** GIOTTO - Mag P/Halley — Day 438, 0515:00 - 0521:00 Universal Time (SCET) — Halley

1. $\Delta B/B_0$ for all waves are ~1
2. All three cases are compressive waves
3. None of the waveforms are sinusoidal
4. The high frequency components at GZ are spatially located
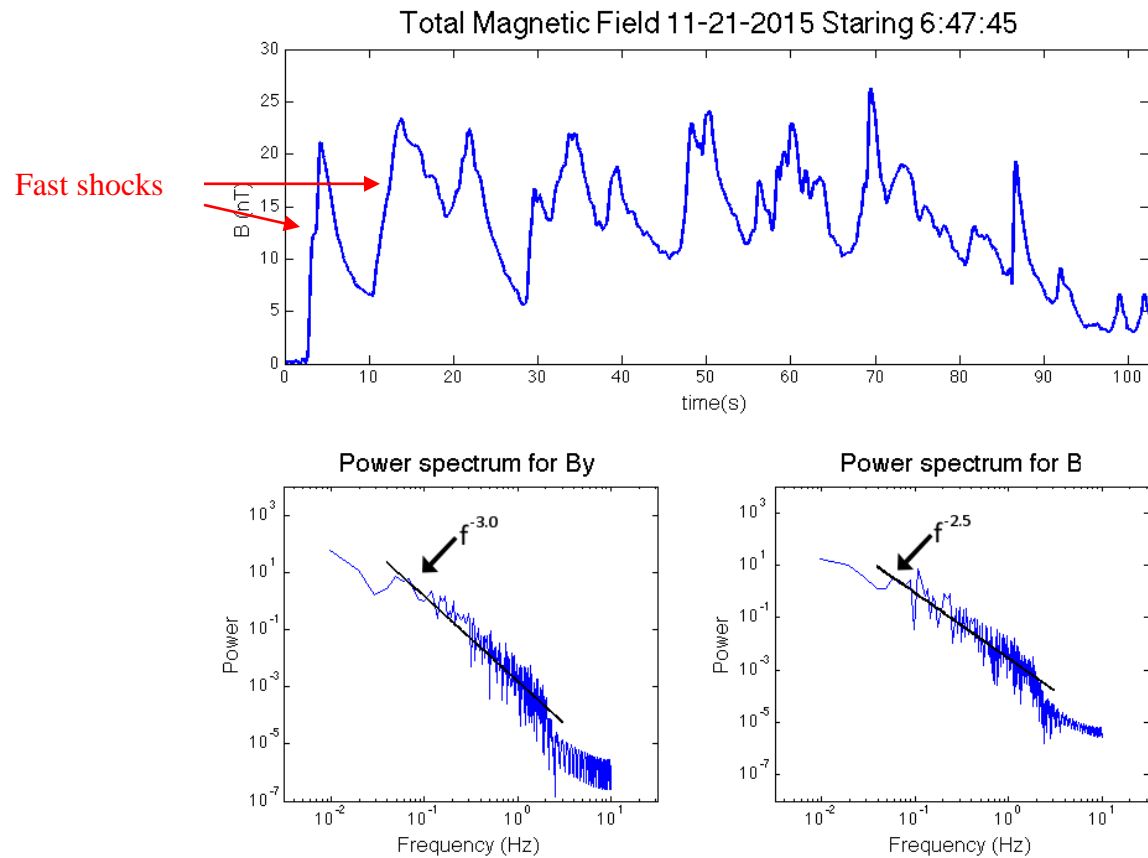
GRL, 1995

Helicity

Not shown
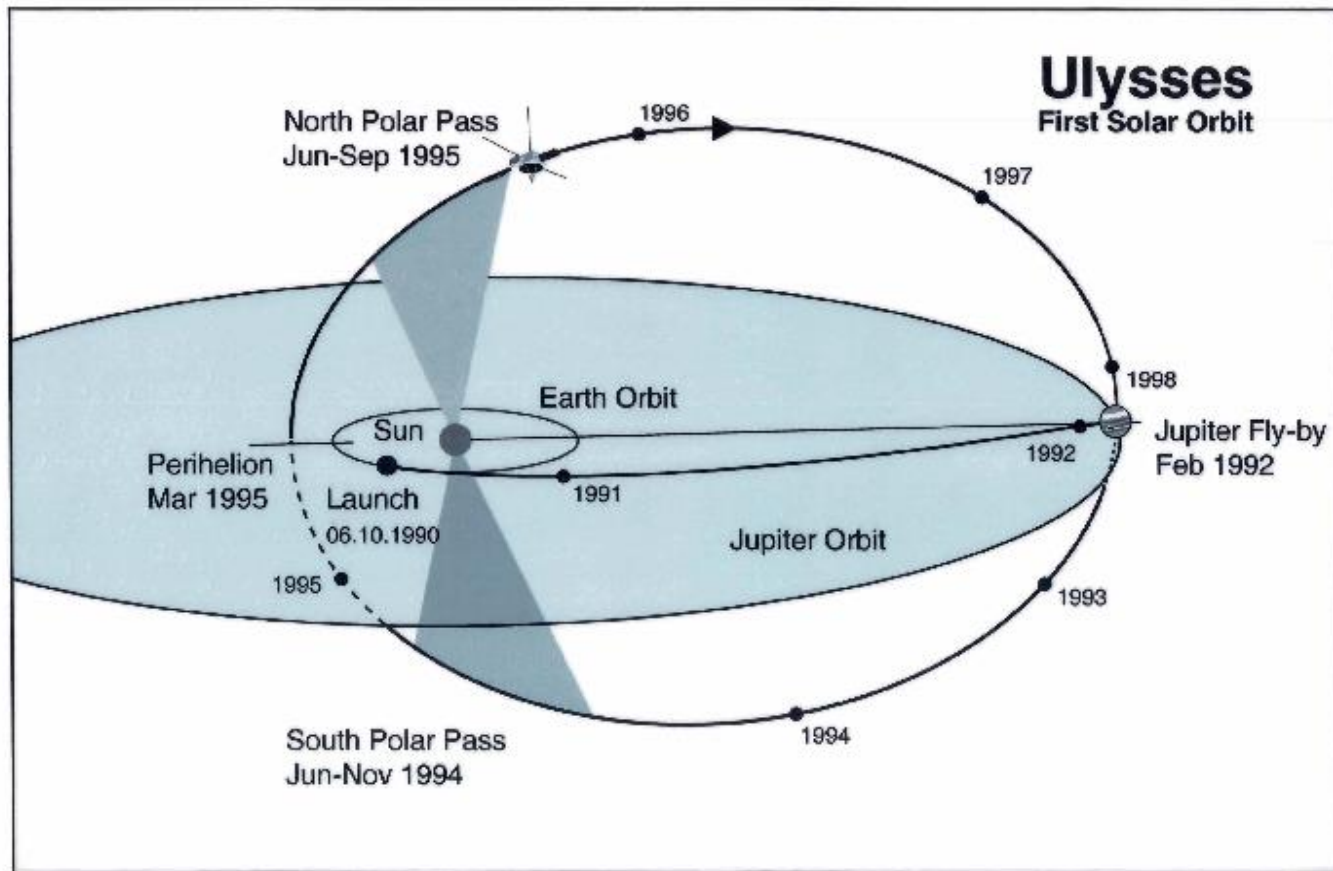
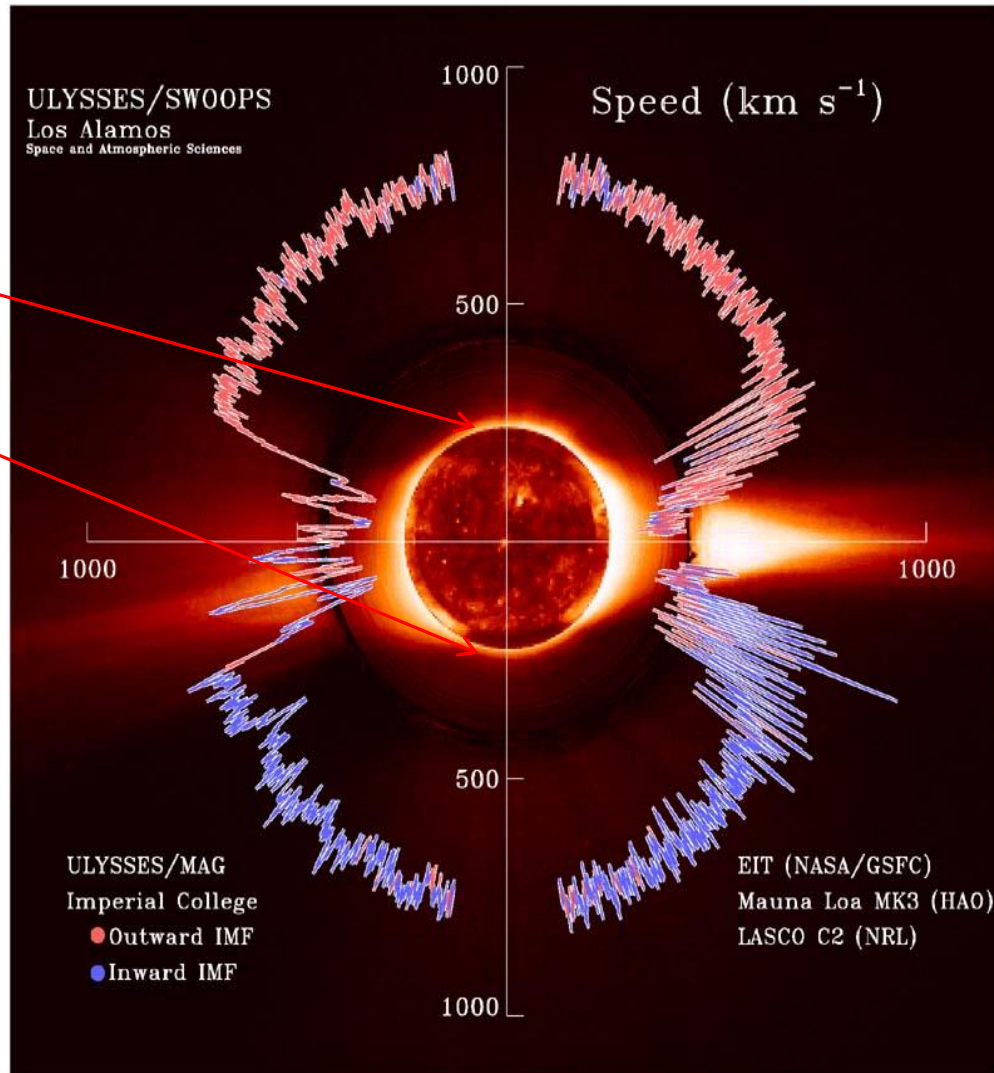All three comets different

Rosetta "Singing Comet" Waves
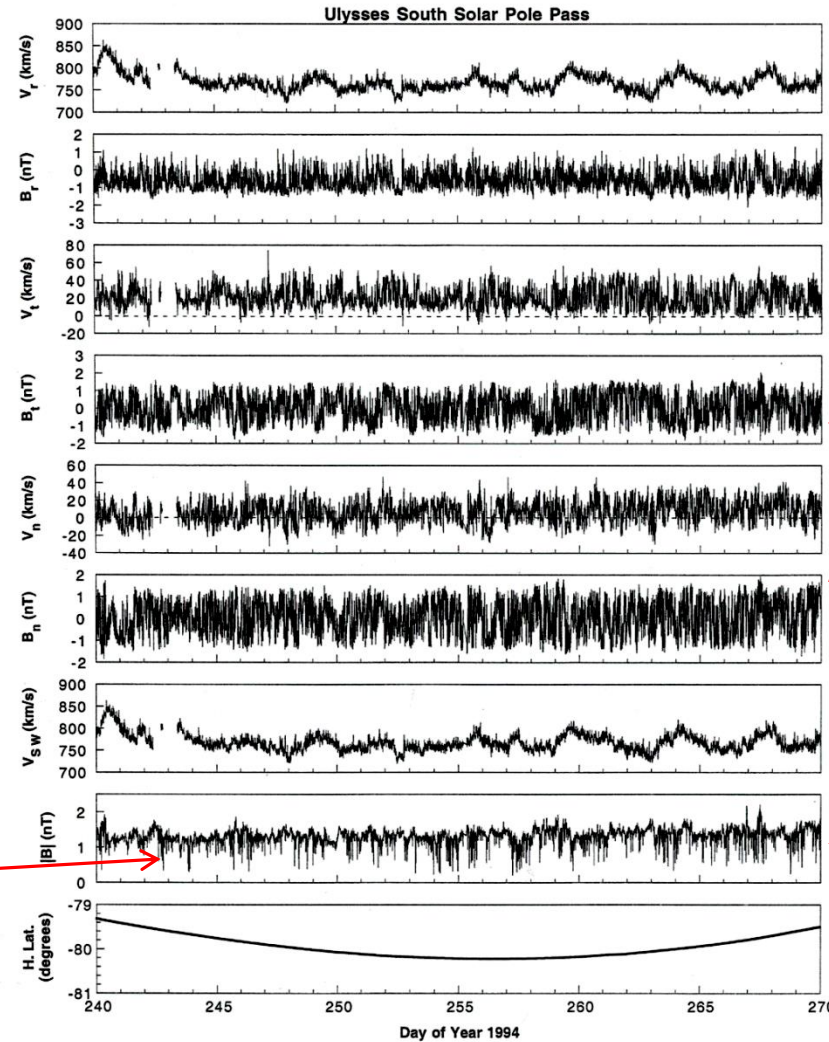
Rosetta Comet Churyumov-Gerasimenko Power Spectra

The NASA/ESA Ulysses Mission: First Mission Over the Sun's Poles

The Solar Wind at Different HelioLatitudes

polar coronal holes during the declining phase of solar cycle

Alfvén Waves over the Southern Solar Pole

Ulysses South Solar Pole Pass

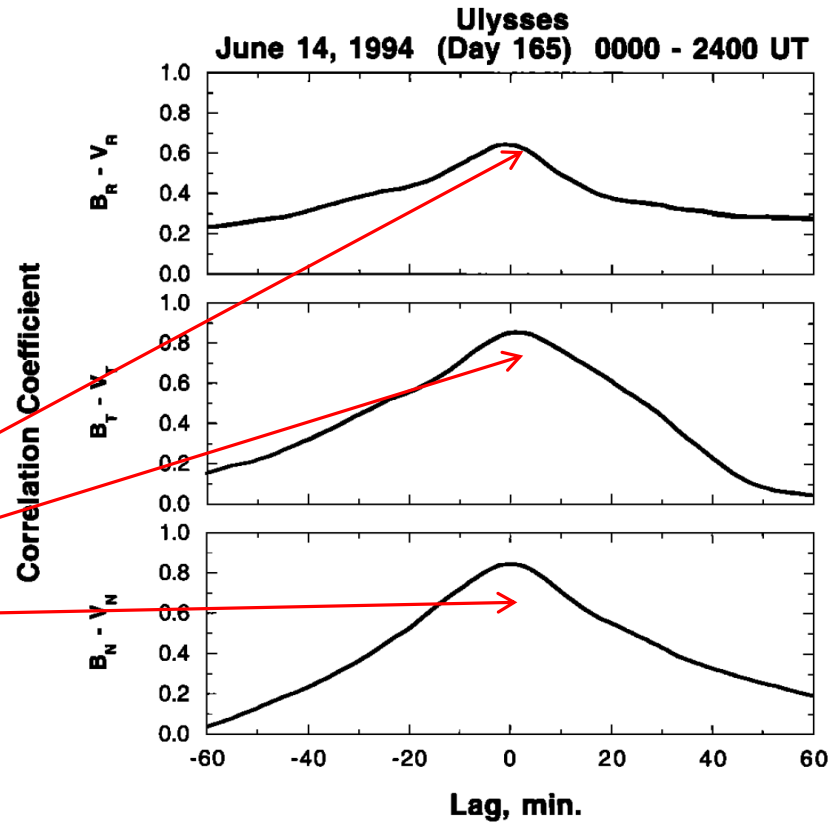ΔB/B$_o$ ~ 1 to 2

B$_o$ = ~ 1.2 nT

Note large magnetic decreases without increases

Interplanetary Alfvén Waves

V_i-B_i correlations proving these waves are Alfvénic: technique by Belcher and Davis, JGR 1971

Tsurutani et al., Astron. Astrophys, 1996; Plas. Phys. Cont. Fus. 1999

General Features of the Interplanetary Medium

Alfvén waves are the predominant wave mode in the interplanetary medium. Hardly any other wave mode of significance has been noted.

The waves are highly nonlinear.

The interplanetary medium is highly compressive (MDs). The field magnitude mainly decreases, not increases.

Following Landau and Lifschitz, 1960

	MASS FLUX	CHANGE IN MAGNETIC FIELD
TYPE OF DISCONTINUITY	ρV_n	$[\vec{H}]$
ROTATIONAL DISCONTINUITY	$\neq 0$	$[H_t] = 0 \quad H_n \neq 0$
TANGENTIAL DISCONTINUITY	0	$[\vec{H_t}] \neq 0 \quad H_n = 0$
SHOCK	$\neq 0$	$[\vec{H_t}] \neq 0 \quad H_n \neq 0$ $[H_t] \neq 0$
CONTACT DISCONTINUITY	0	$[\vec{H_t}] = 0 \quad H_n \neq 0$

"t" is tangential comp.
"n" is normal comp

Not found in space plasmas. Will not discuss further

Adapted in Tsurutani et al., NWCSP, Hada and Matsumoto, 1997

MHD Shock Subcategories

- Shocks*: Fast ($V_s > V_{ms}$)

  Intermediate ($V_{interm} < V_s < V_{ms}$)

  Slow ($V_{sonic} < Vs < V_{interm}$)

*The shock normal is first determined. Then Rankine-Hugoniot relations are used to get the shock velocity along the normal.

Shocks: Forward

Reverse

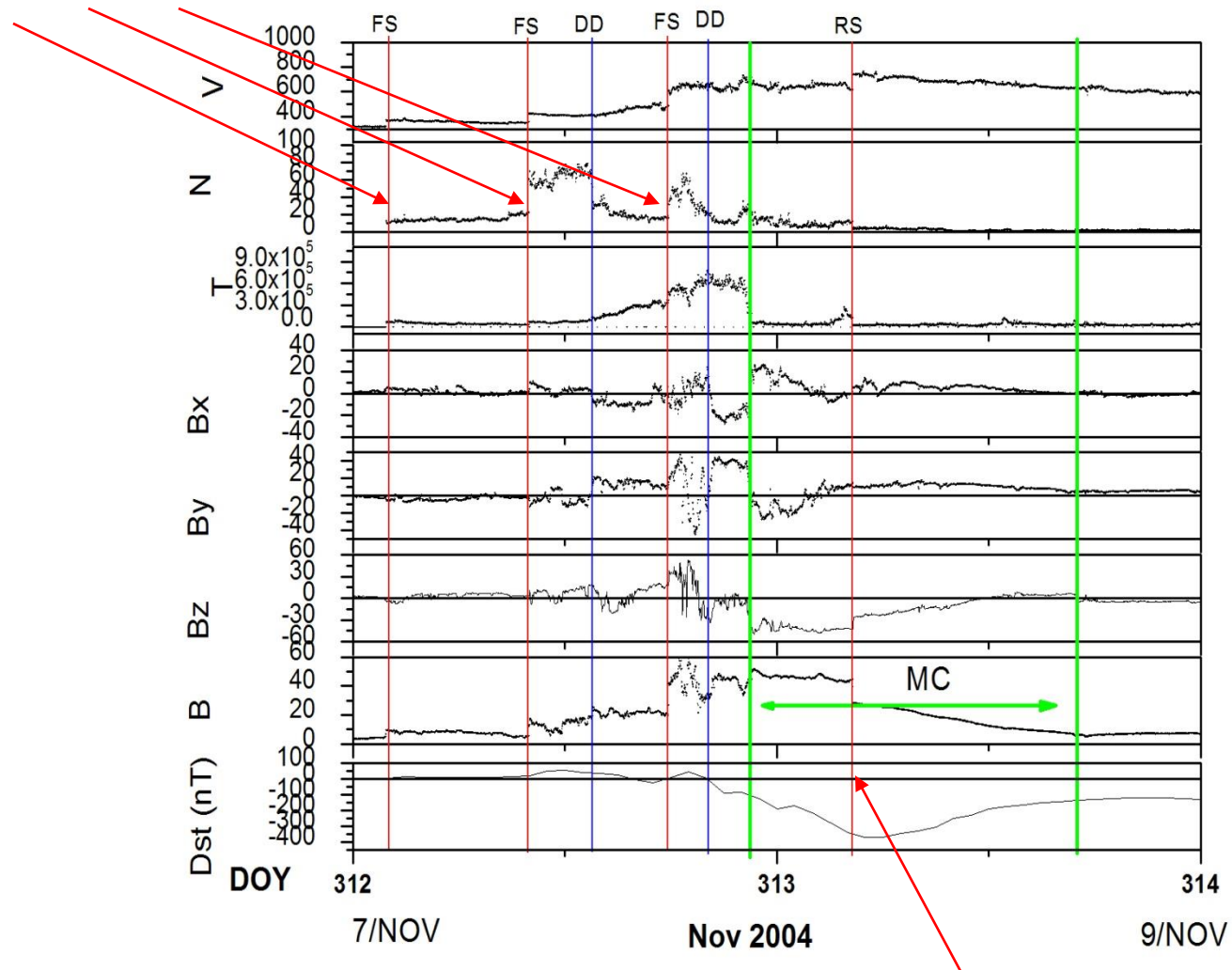(see Petschek, *Rev. Mod. Phys*, 1958; Tsurutani et al. JASTP, 2011)

What Type of Shocks Are Detected in Interplanetary Space?

SHOCK

Fast Forward Shock

ICME/DRIVER GAS

SHEATH
(shocked slow solar wind)
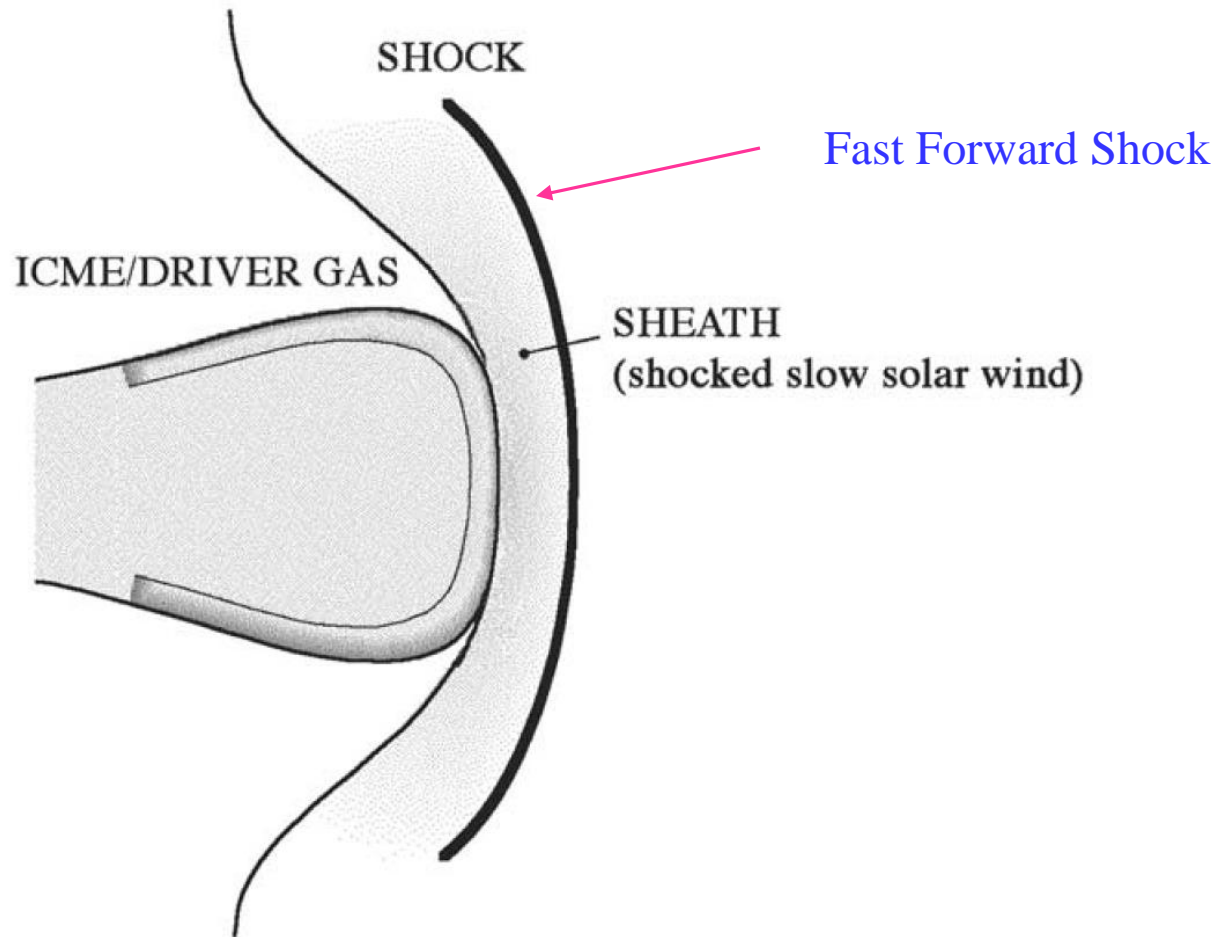
Blast wave (undriven) shocks have not been
detected. However closer to the Sun will it be different?

CAWSES I 7-8 NOV, 2004

Fast Forward Shocks
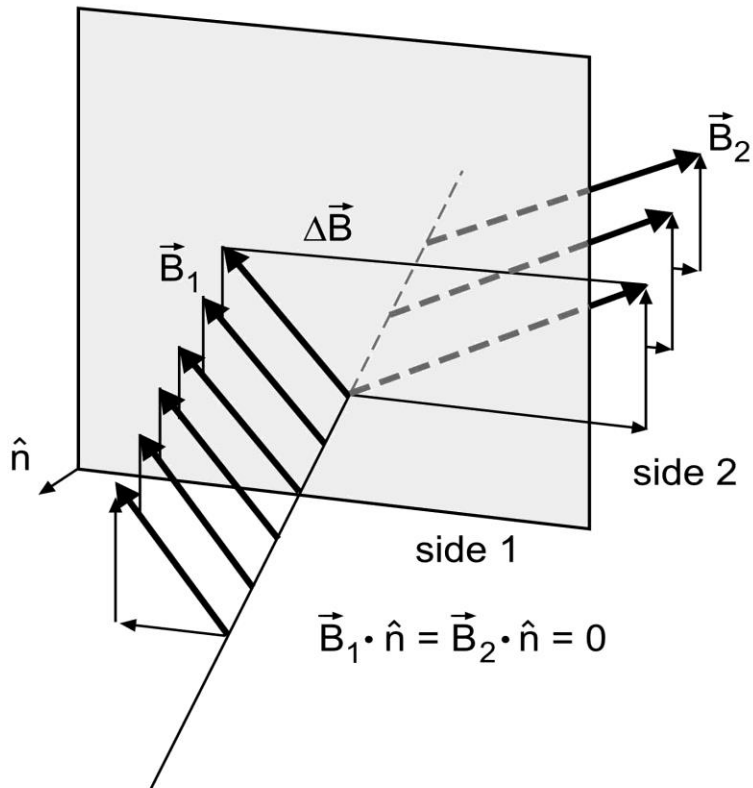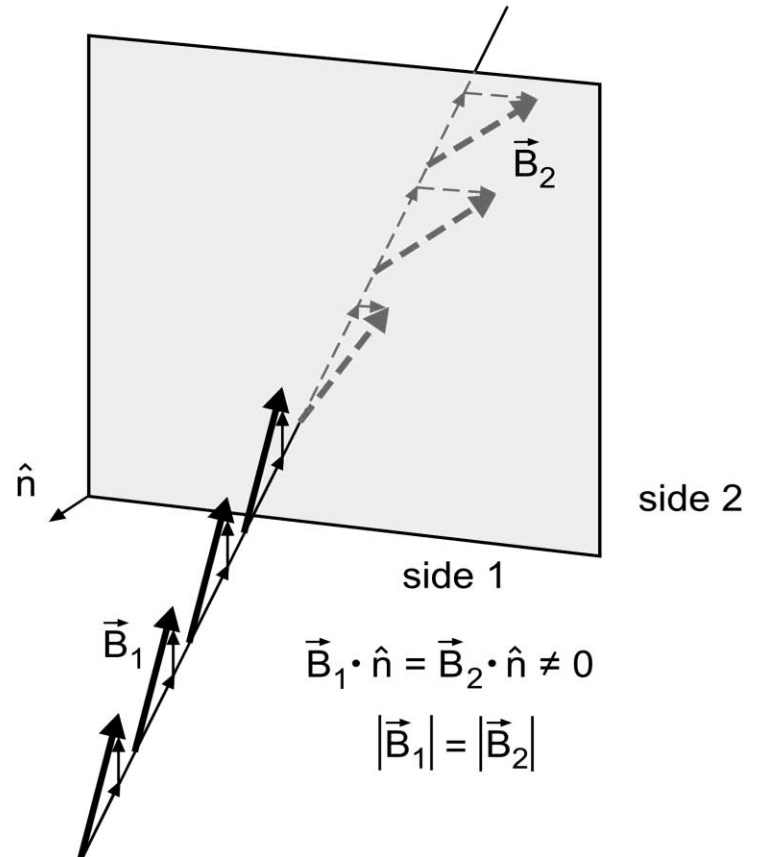

A reverse wave (not a shock) causes the onset of the storm recovery phase

Tsurutani et al., GRL, 2008

RDs or TDs (DDs) Rate of 1 or 2/hr

Tangential Discontinuity

$\hat{n}$

$\vec{B}_1$

$\Delta\vec{B}$

$\vec{B}_2$

side 2

side 1

$$\vec{B}_1 \cdot \hat{n} = \vec{B}_2 \cdot \hat{n} = 0$$

Rotational Discontinuity

$\hat{n}$

$\vec{B}_2$

side 2

side 1

$\vec{B}_1$

$$\vec{B}_1 \cdot \hat{n} = \vec{B}_2 \cdot \hat{n} \neq 0$$

$$\left|\vec{B}_1\right| = \left|\vec{B}_2\right|$$

Tsurutani et al., Non Waves Chaos Space, Hada, Matsumoto eds, 1997

"Directional Discontinuity" (Either RD or TD) Criteria: Automatic Selection by Computer
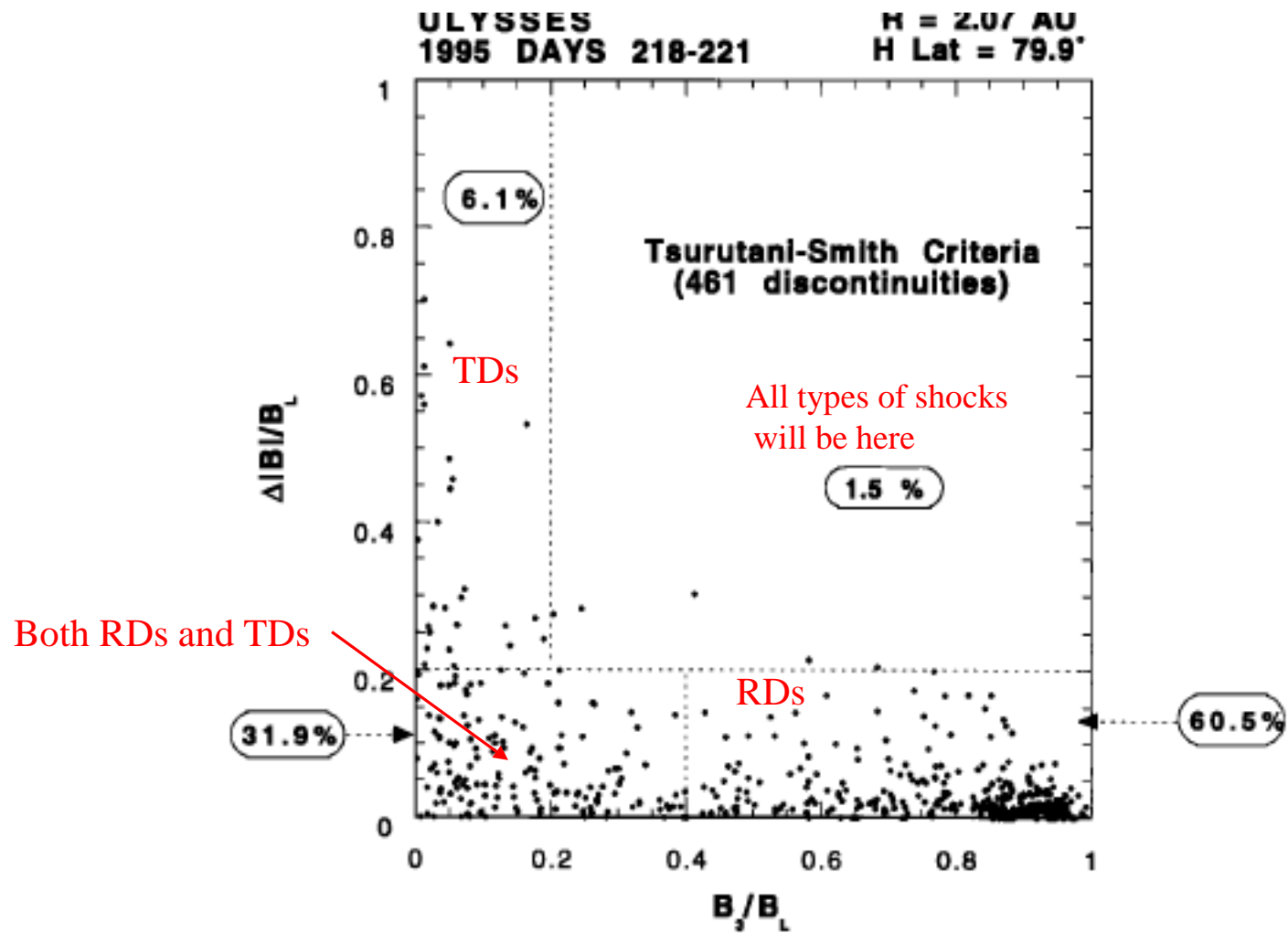
- $\Delta\mathbf{B}/B_L > 0.5$ (Tsurutani and Smith, JGR, 1979)

- $\theta = \cos^{-1}(\mathbf{B}_1 \times \mathbf{B}_2/|\mathbf{B}_1||\mathbf{B}_2|) \geq 30^\circ$ (Lepping and Behannon, JGR, 1986)
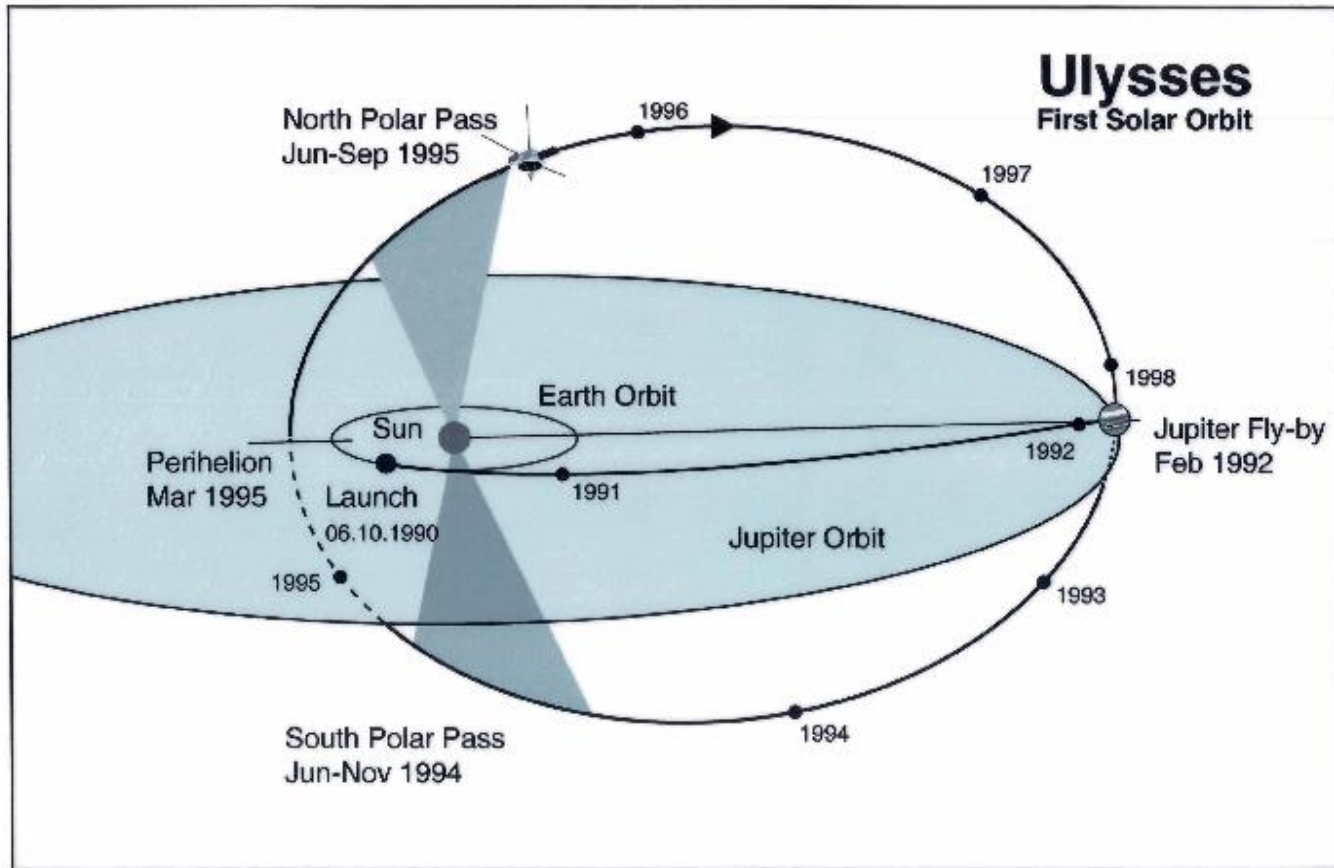
E. Smith (JGR 1973a,b) Method of Separating RDs from TDs
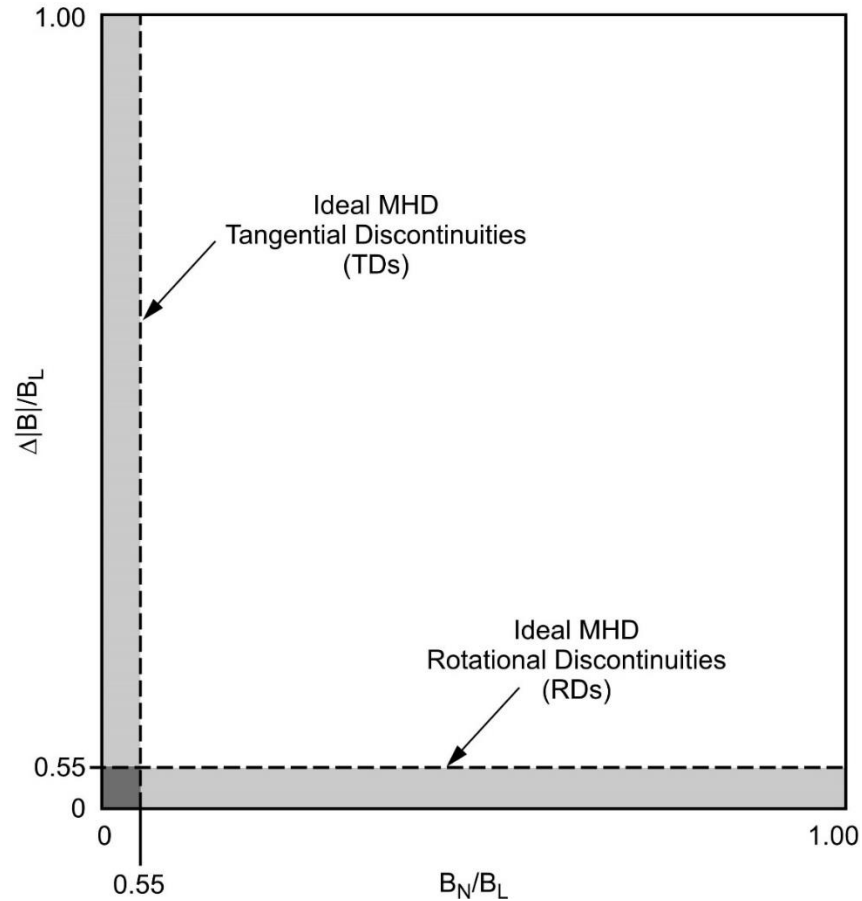
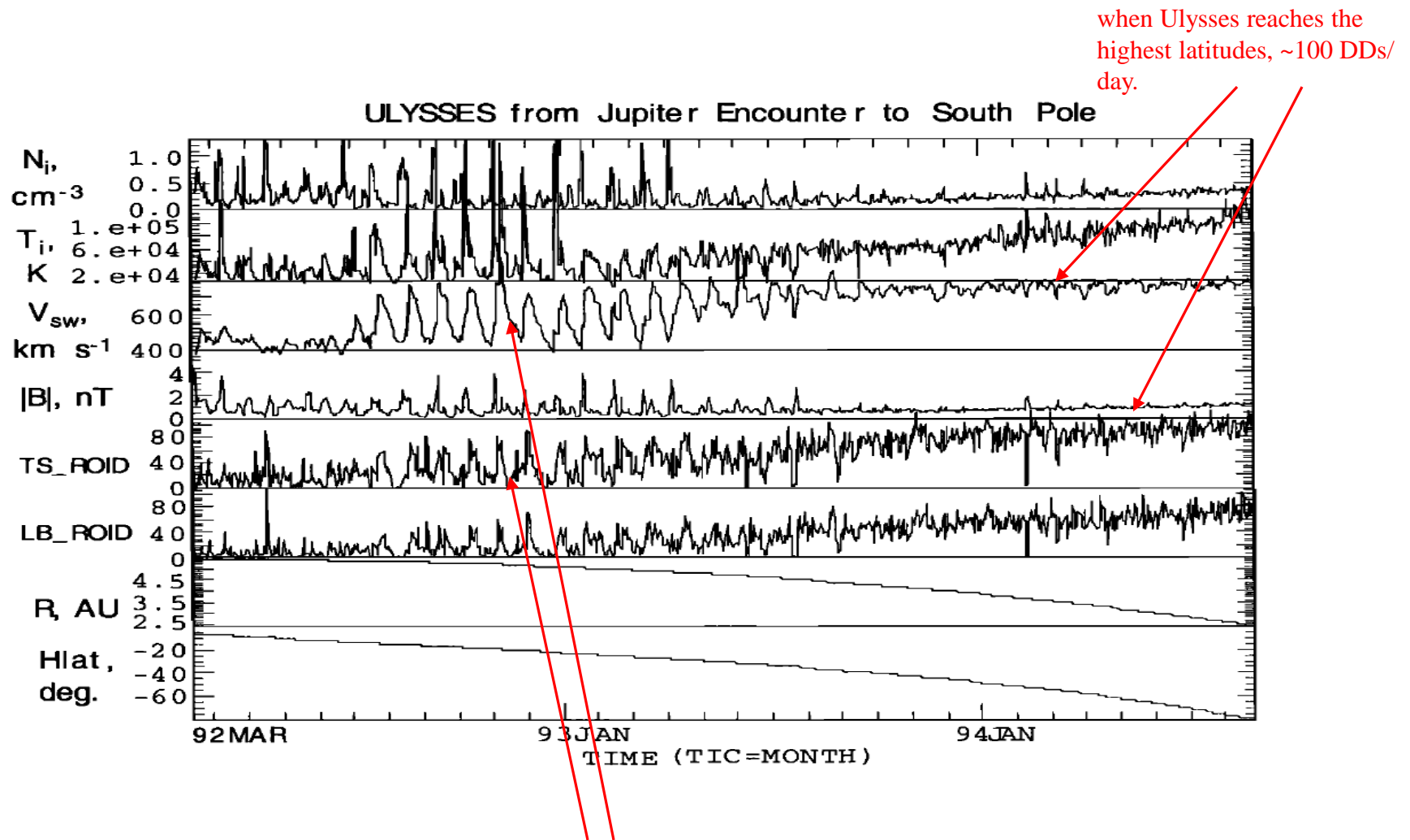B_L is the larger field magnitude on either side of the discontinuity

Adapted for the Smith criteria

ULYSSES
1995 DAYS 218-221
R = 2.07 AU
H Lat = 79.9°

Tsurutani-Smith Criteria
(461 discontinuities)

6.1%

TDs

All types of shocks will be here

1.5 %

Both RDs and TDs

RDs

31.9%

60.5%

$\Delta|B|/B_L$

B_3/B_L

Tsurutani et al. Astr Astro, 1996

The NASA/ESA Ulysses Mission

Ulysses Ecliptic Plane:
Discontinuities and High Speed Streams

when Ulysses reaches the highest latitudes, ~100 DDs/day.
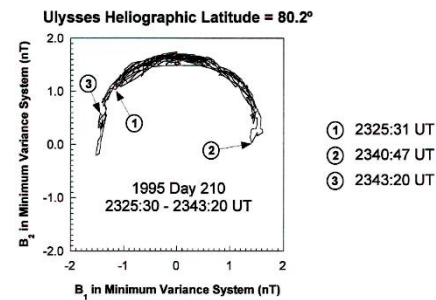

ULYSSES from Jupiter Encounter to South Pole

Discontinuity occurrence rate correlated with solar wind speed

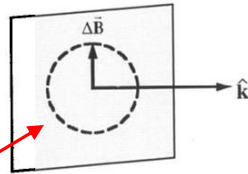# What Do These Nonlinear Alfvén Waves Look Like?
(They Are Not Sinusoidal)
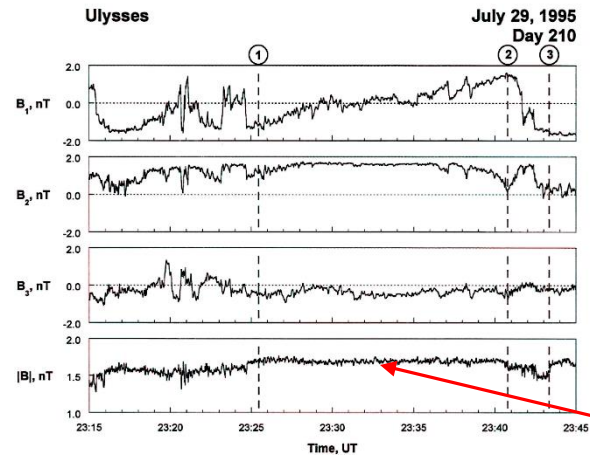
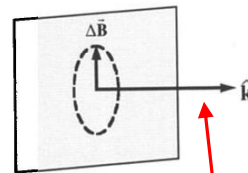roughly constant magnetic field magnitude

nonlinear phase-steepened Alfven wave: arc polarization

Tsurutani et al. GRL 1994; Plas. Phys. Cont. Fusion, 1997; RG, 1999

Analogy of Spherical Waves to Planar Waves

Planar Waves

Spherical Waves
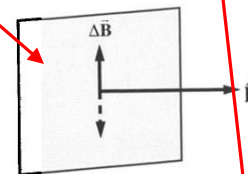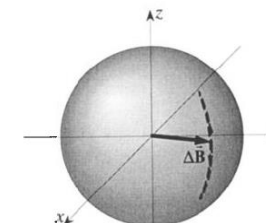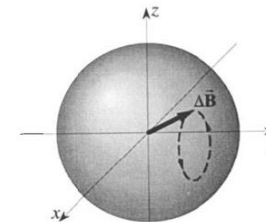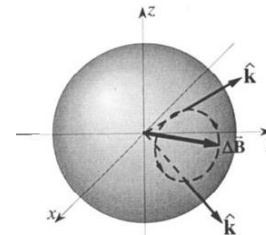
Circular Polarization

Elliptical Polarization

Linear/Arc Polarization

a)

b)

The perturbation vector rotates in the surface of a plane

The wave direction of propagation k is in the minimum variance direction.

Tsurutani et al., Plas. Phys. Cont. Fus. 1997; RG, 1999

The wave (phase) steepening process is creating a wave spectrum

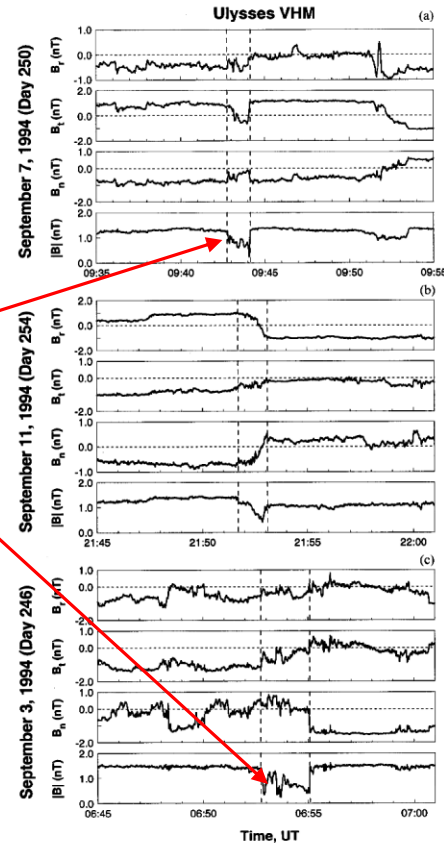The front edge contributes a high frequency component

The trailing part contributes longer period components (period doubling)

What Is the Magnetic Compressibility in the Interplanetary Medium?
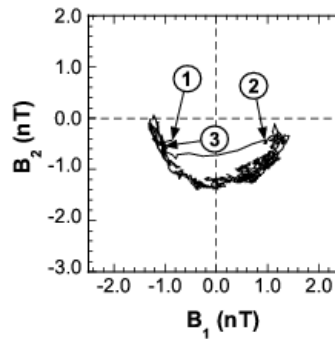
3 Examples of Magnetic Decreases

Note sharp edges to MDs

There have been many suggestions on what causes MDs.
All agree that they are not part of the Alfven wave itself

The Relationship between Alfvén waves and MDs

nonlinear Alfvén waves
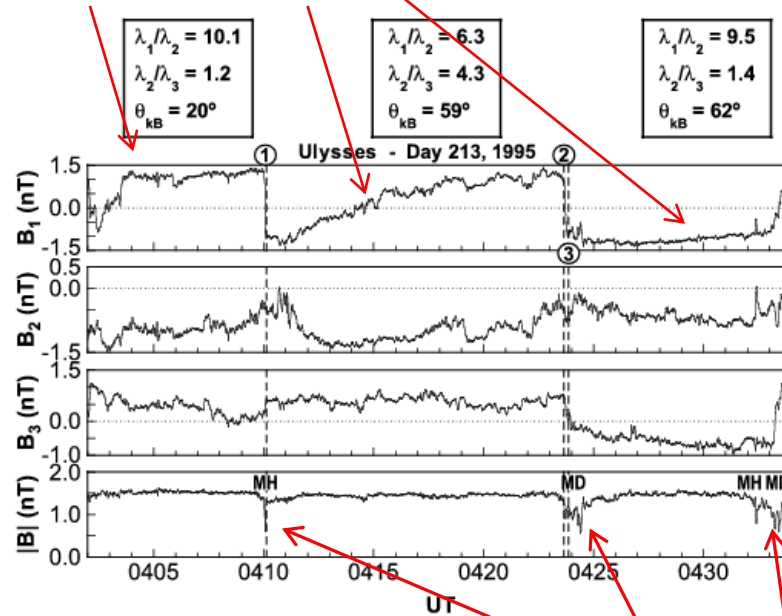
magnetic decreases located
at the edges of the Alfvén waves

GRL, 2002

The Smith Discontinuity Phase Space Plot for MDs

A Mess! Why are all these points so scattered?

Ulysses South Pole
Days 242-268 1994

Tsurutani and Ho, RG, 1999
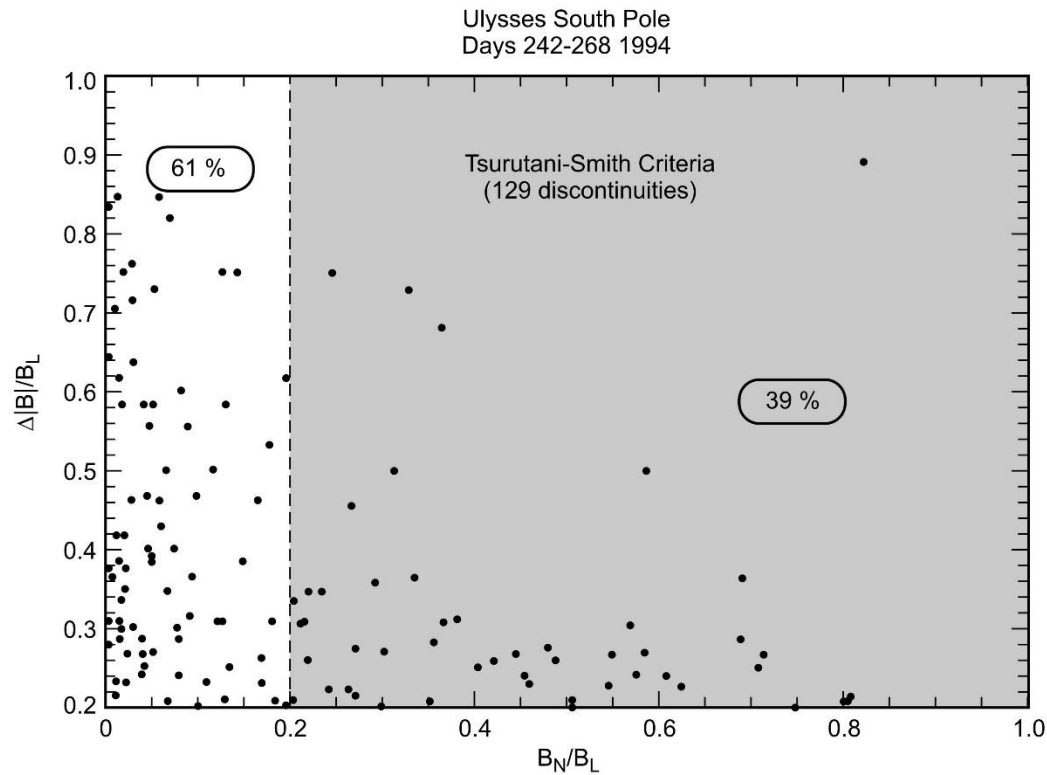
Distribution of Protons $T_{inside\ MD}/T_{outside\ MD}$ Ratios
Ulysses North Pole

Ulysses - Days 208-216, 1995
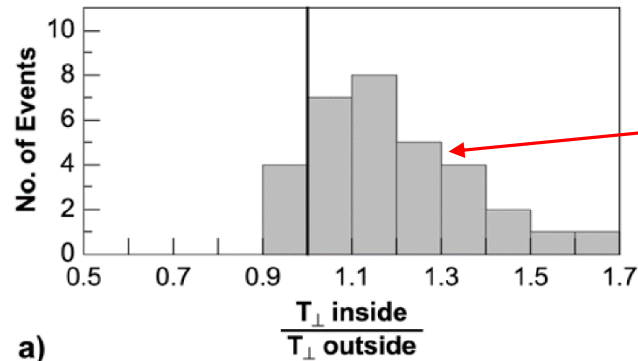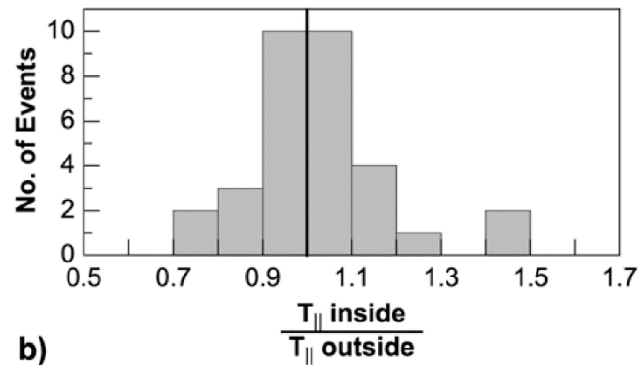
Local ion heating

Our interpretation is that MDs are created by the Ponderomotive Force associated with the steepened Edges of the Alfven waves

Tsurutani et al. GRL 2002b

Local Ion Heating Causes Growth of Plasma Waves

Proton cyclotron waves

Ulysses – 2001 Day 286

Ulysses - 2001 Day 280
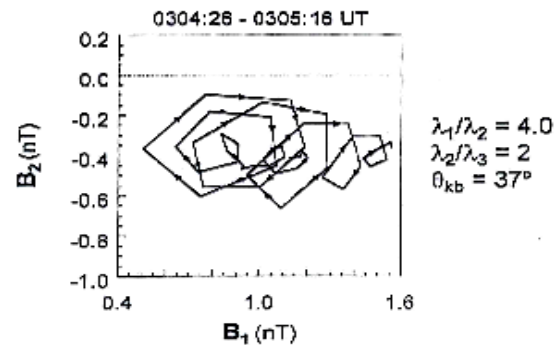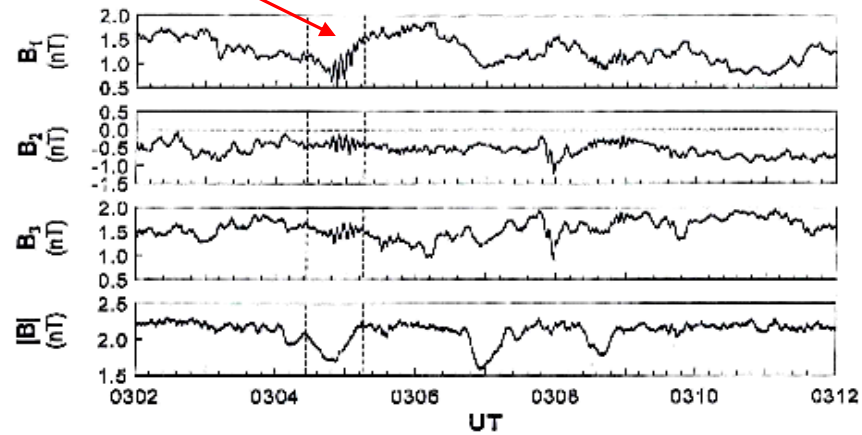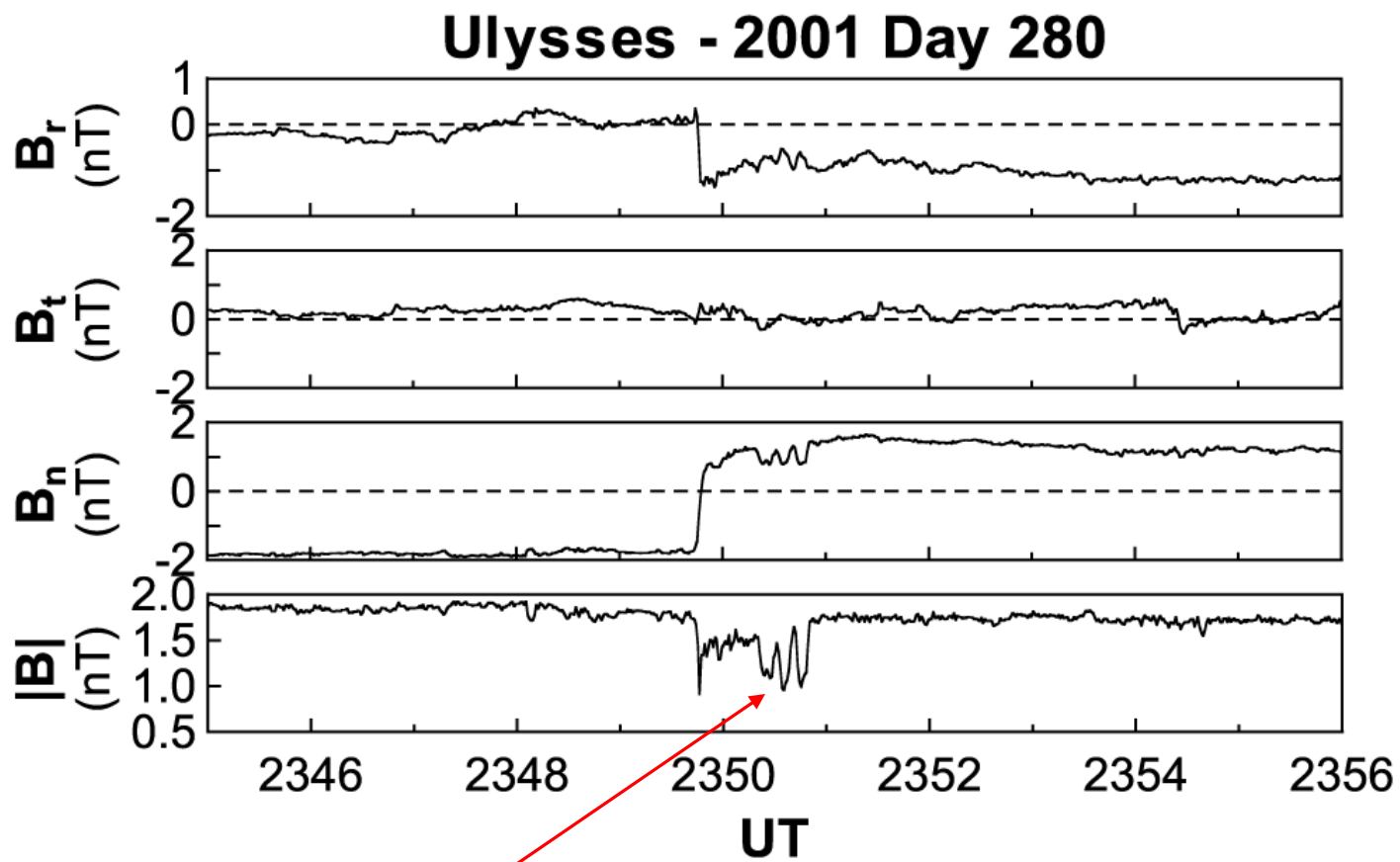
Mirror mode waves generated by $T_\perp/T_\parallel > 1$ instability

27 Jul 1995 (day 208)

Langmuir waves

Electron whistler mode waves

N. Lin et al. GRL 1995
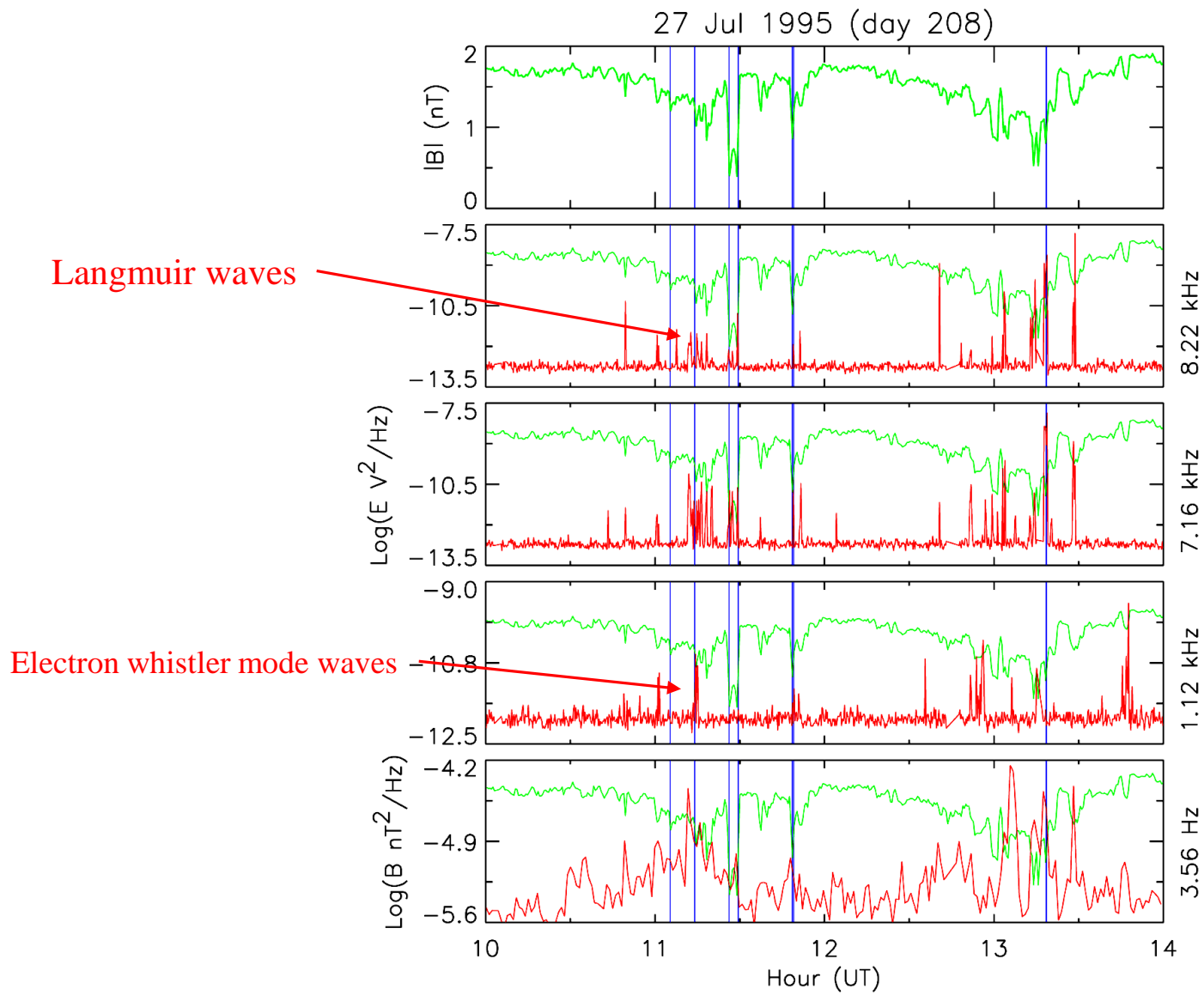
Scenario

- The ions (and electrons) are heated by the Ponderomotive Force associated with the steepening of the Alfvén waves (Dasgupta et al. GRL 2003). This is the dissipation process of the Alfvén waves.

- Magnetic decreases (MDs) are created by the diamagnetic effect of the heated ions (and electrons) (Tsurutani et al. GRL 2002a, b). The heated plasma "pushes out" the ambient fields.

- Can these Alfvénic structures be intermediate shocks? They are steepened and they show dissipation.

- The picture is actually more complicated. The edges of the MDs have been suggested to be slow shocks by Farrugia et al.

How Fast Are the Alfven Waves and MDs Evolving?

0.01 AU

ACE
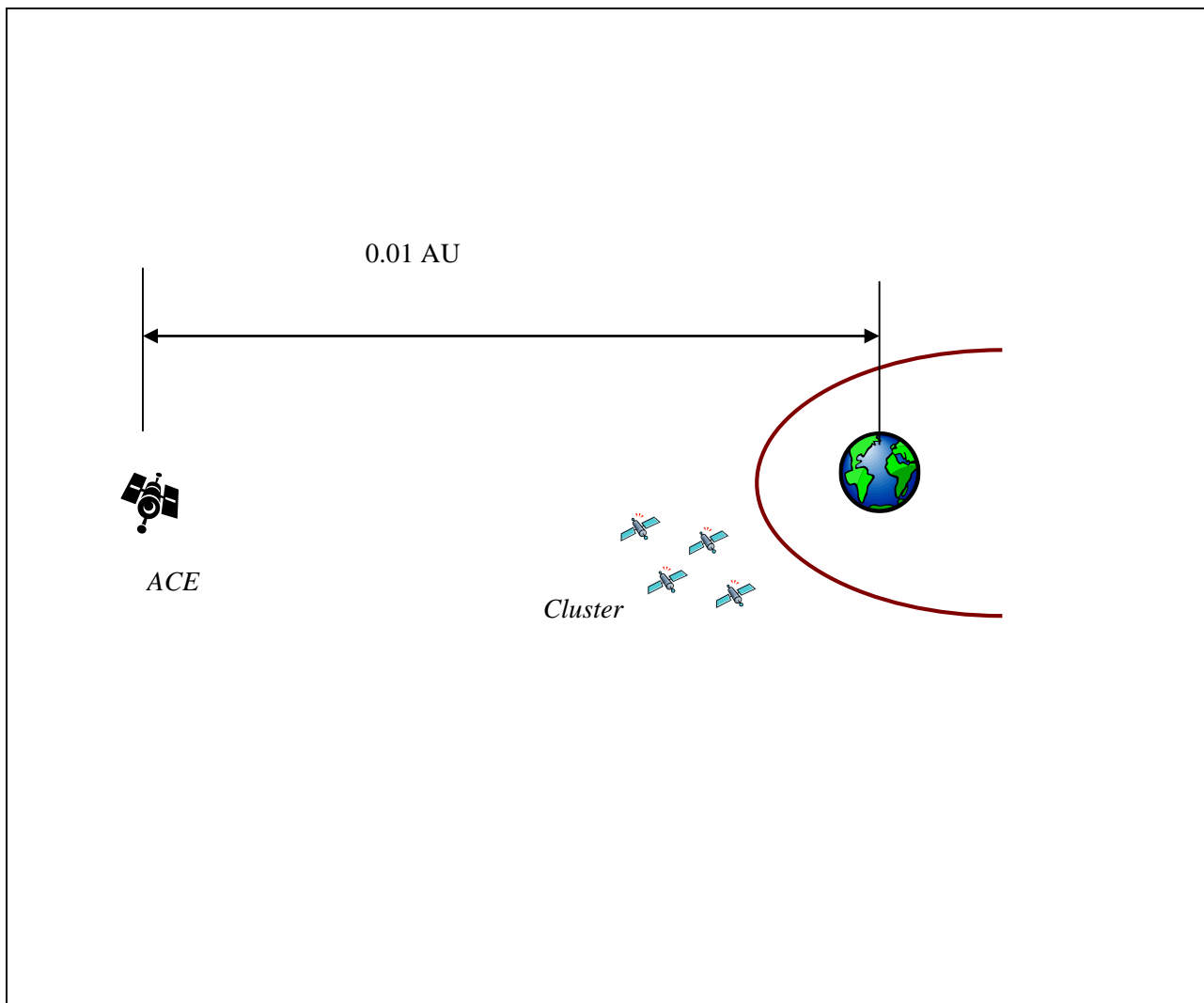
Cluster

Day 43, 2001
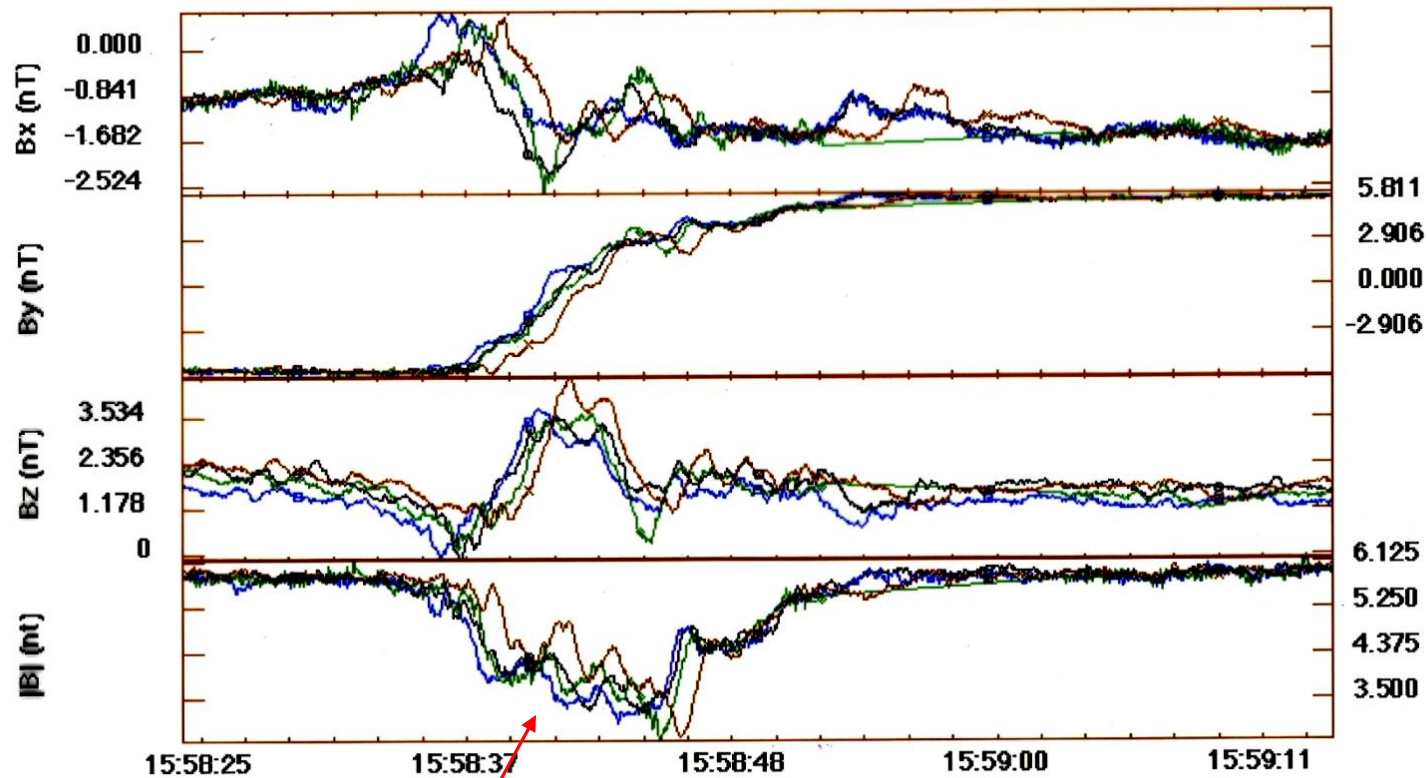
4 Cluster S/C measurement of a MD

Rate of Phase Steepening

Event (Day)	MD-ACE/ MD Cluster
33-34	--
43	4.4
50	5.8
51(a)	5.0
51(b)	14.5
76-77	21.3
77	5.5

MDs and Alfvén waves are evolving rapidly in time and space!

What Are These Discontinuities at the Edges of Alfvén Waves? Scenario

Alfvén wave phase-steepen into rotational discontinuities

As they steepen further, they will form intermediate shocks

As the Alfvén waves dissipate they form MDs, which are nonpropagating structures.

The sharp edges of the MDs may be slow shocks

Since slow shocks propagate slowly, they may be misinterpreted as tangential discontinuities

What is the Source of the Alfvén Waves?

It used to be thought that supergranual circulation at the Sun was the source.

However with Alfvén waves shown to being spherical in nature (close to the source) and shown to evolve rapidly, local generation must also be occurring.

Hellinger and Travnicek (2008, 2011, 2013) have suggested the oblique fire hose instability with several sources of free energy.

# Summary of Interplanetary High Speed Solar Wind "Alfvénic Turbulence"

- Phase-steepening of Alfvén waves place wave power into higher and lower frequencies at the same time. The high frequency component is similar to wave breaking. The low frequency component is period doubling.

- The arc polarized Alfvén waves split into two parts. Both parts are coherent.

- The Alfvén waves are spherical in nature. They are continuously being generated in the solar wind, replacing dissipated energy.

- The dissipation of the waves by the Ponderomotive Force are creating nonpropagating magnetic compressions (MDs), i.e., the compressional part of the interplanetary medium.

- Speculation: Intermediate and slow shocks are present and are a major part of the turbulence.

Thanks for You Attention.

The End

Effects of Magnetic Compressibility Has on Solar Flare Energetic Ions: A New Concept Called Nonresonant Particle Scattering

Nonresonant Energetic Particle-Structure Interactions

Proton Gyromotion

Magnetic Decrease (MD)
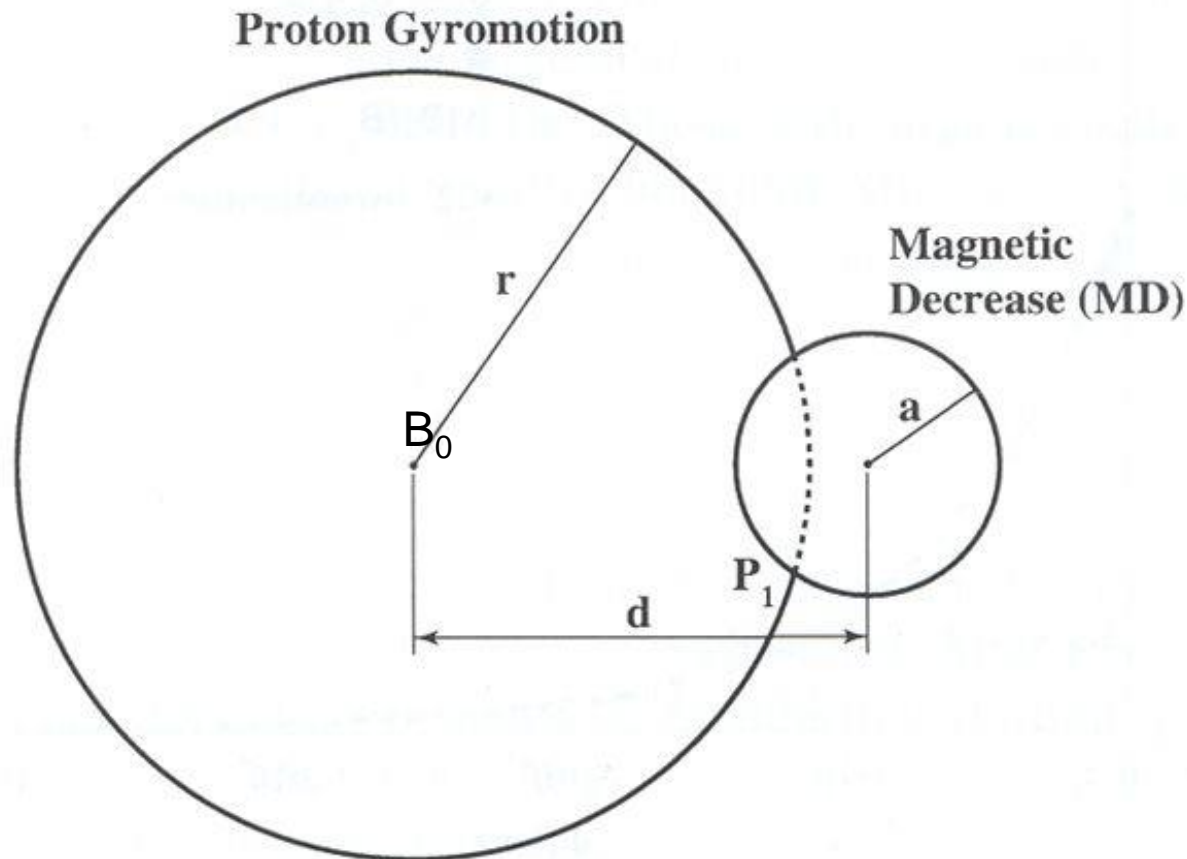
Tsurutani et al., NPG, 1999

r = particle gyroradius

a = MD radius (assume circular cross-section, constant field B_{MD})

d = "impact parameter"

Particle Cross-field diffusion
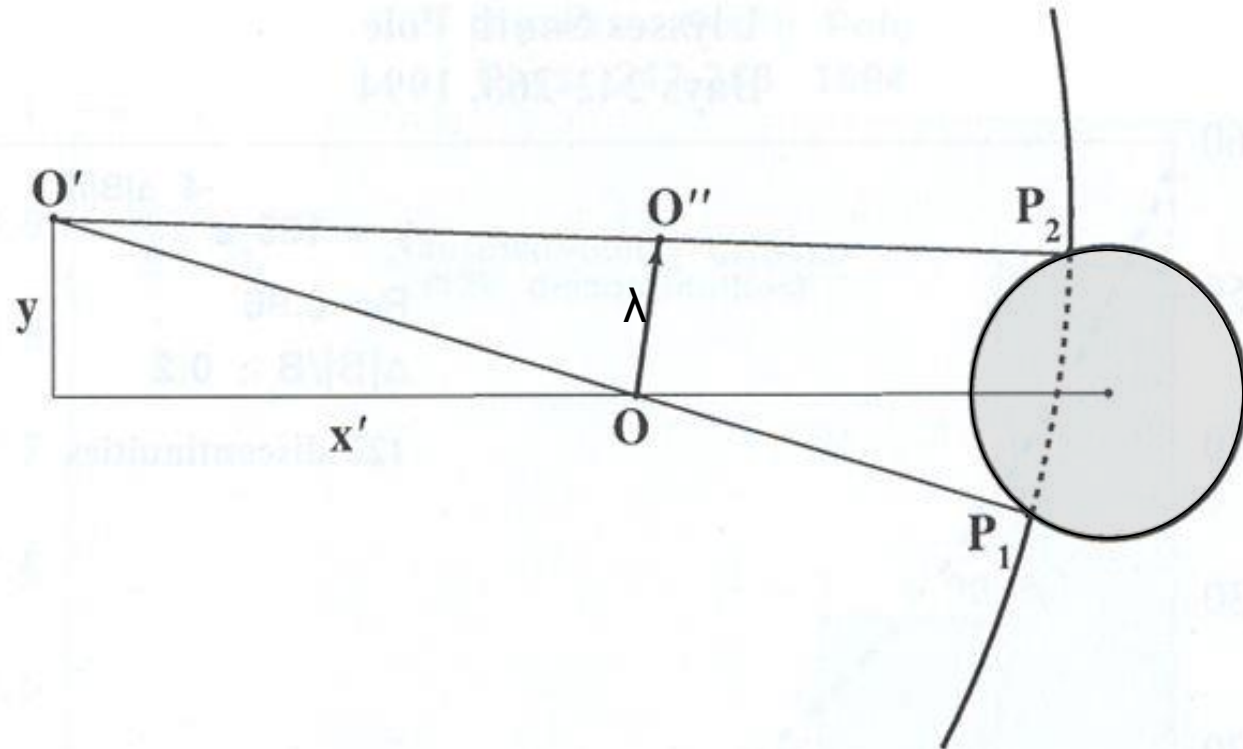
The amount of cross-field transport in this particle- MD interaction is the distance between
0 and 0". We will call this distance λ.

Geometry Used to Get λ as a Function of r, B_o, B_{MD}, a and d

Proton Gyromotion

Magnetic Decrease (MD)

B_O is the ambient magnetic field strength
B_{MD} is the magnetic field strength inside the MD

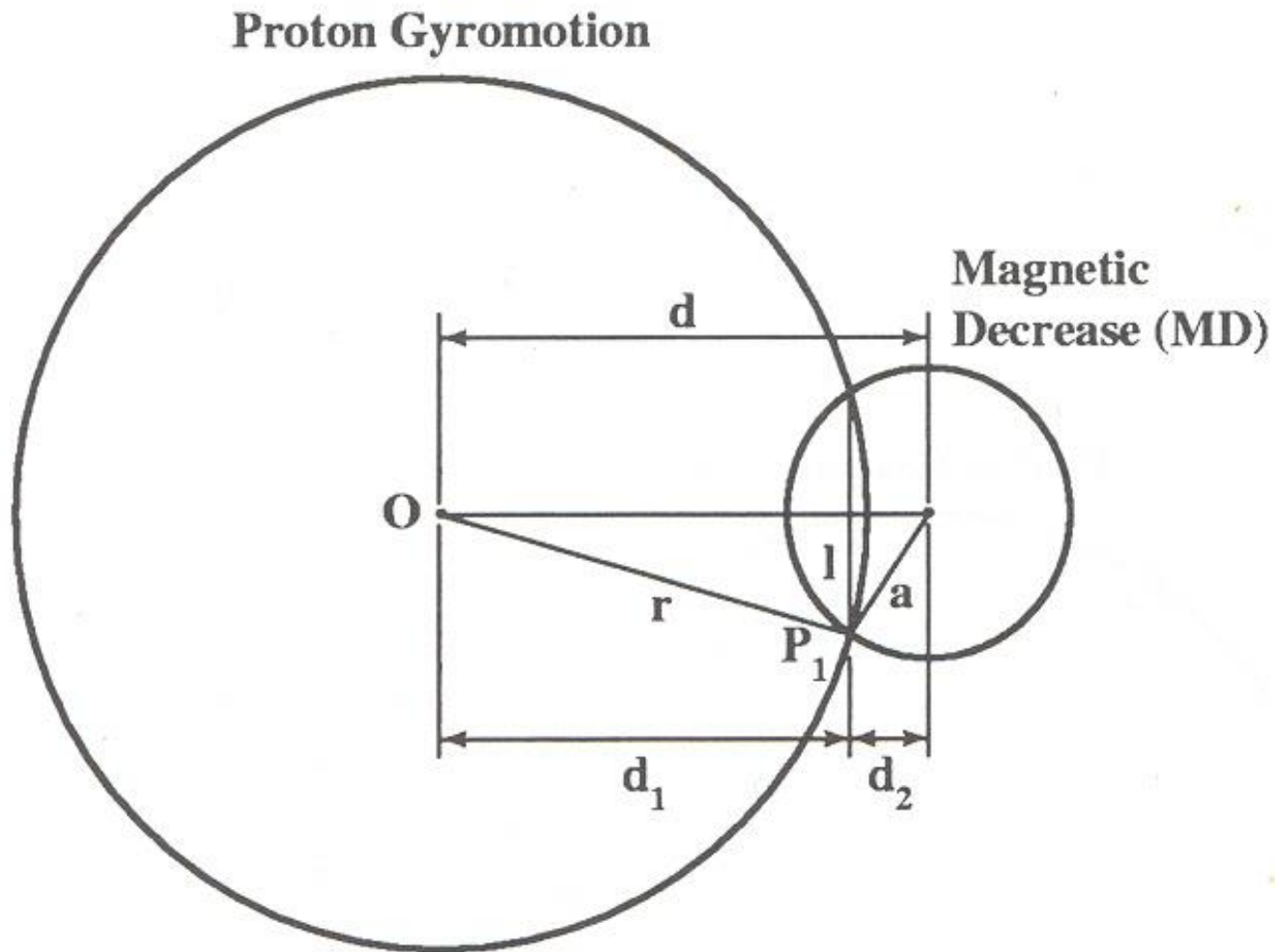# An Analytical Expression for Cross Field Diffusion

$D_\perp = (\lambda^2)/\Delta t$ where Δt is the time between collisions

$$D_\perp = \frac{(M-1)^2}{2aM^2\Delta t}\left[\frac{2a}{3}([2M+3]\,a^2 + 3M^2r^2) + \frac{(a^2 - M^2r^2)^2}{[M(M-1)(a^2-Mr^2)]^{\frac{1}{2}}}\tanh^{-1}\left(\frac{2a\left[M(M-1)(a^2-Mr^2)\right]^{\frac{1}{2}}}{(2M-1)a^2 - M^2r^2}\right)\right],$$

In the above, $M = B_o/B_{MD}$

How does one make an accurate calculation of cross-field diffusion?

Monte Carlo (statistical) calculations

DaCosta et al. *Astrophys. J.*, 2013, INPE PhD thesis

Runs

- A proton kinetic energy is selected. Many runs are made with this same energy.

- Each proton interacts with 100 MDs. Each MD is selected randomly (the characteristics of the MDs determined by data analyses).

- This (above) is run 1,000 times, getting 1,000 values of λ_i.

- The 1,000 values of λ_i are used to empirically calculate the cross field diffusion rates.

100 keV protons diffuse across the magnetic field at 11% of the Bohm rate

2 MeV ions diffuse at 5.5% of the Bohm rate
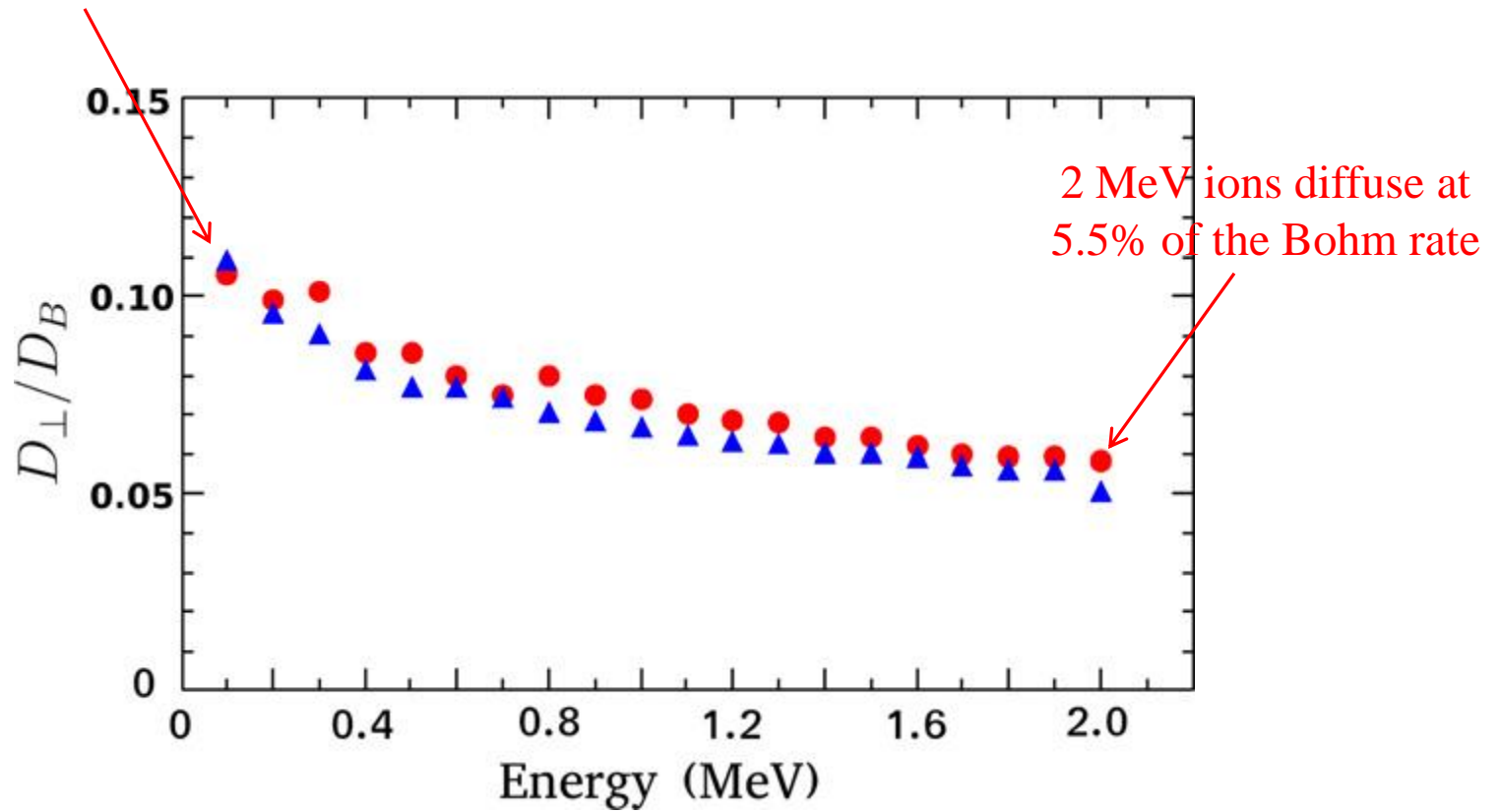
Summary

•MDs can lead to rapid (> $0.1D_{Bohm}$) cross-field diffusion of ~1 MeV protons. This may account for the rapid and broad dispersal of solar flare particles.

•The flare particles associated with the enormous flare that occurred recently on the backside of the Sun was detected at both Stereo spacecraft and the Earth, indicating a 360° longitudinal spread. How else other than rapid cross field diffusion can explain this?

Alfvén Waves and Geomagnetic Activity

May 15-18, 1974
Days 135-138
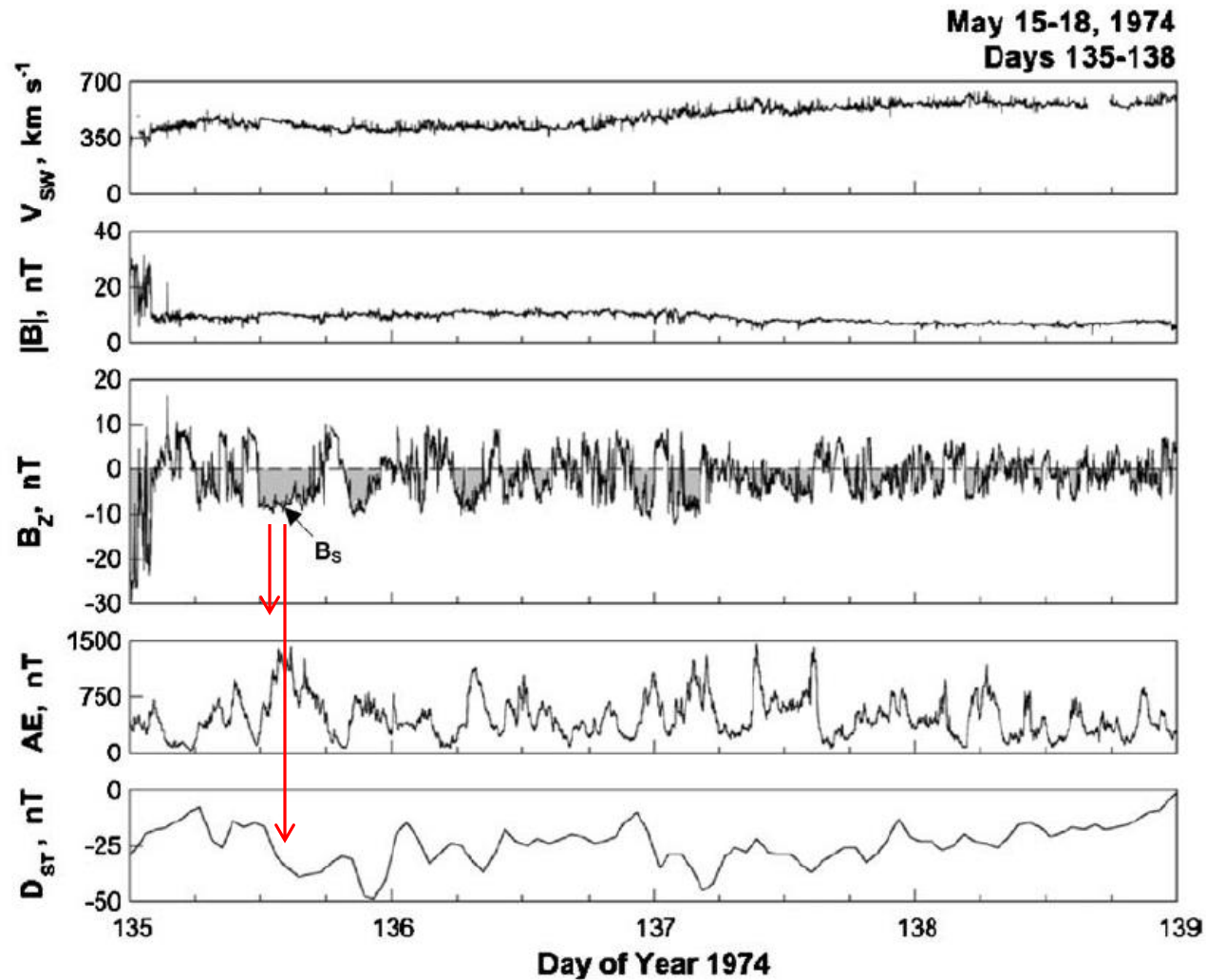
More solar wind energy put in during HSSs than during ICME storms.

JGR, 1995

Earth's Magnetosphere

Sun

+
−

CME

IMF ⟶ Solar Wind

-B$_z$

⊙ ⊗

Storm Plasmasheet Injection

Oxygen Ions

IMF: Interplanetary Magnetic Field

B$_z$: Southward component of IMF

The principal cause of energy transfer from the solar wind to the magnetosphere during magnetic storms is magnetic reconnection (Dungey, Phys Rev. 1961; Echer et al. JGR 2008).

First time chorus, PC5s and relativistic electrons shown together

Relativistic electrons

Akebono chorus

Canadian PC5s

HILDCAA

Tsurutani et al. JGR, 2006
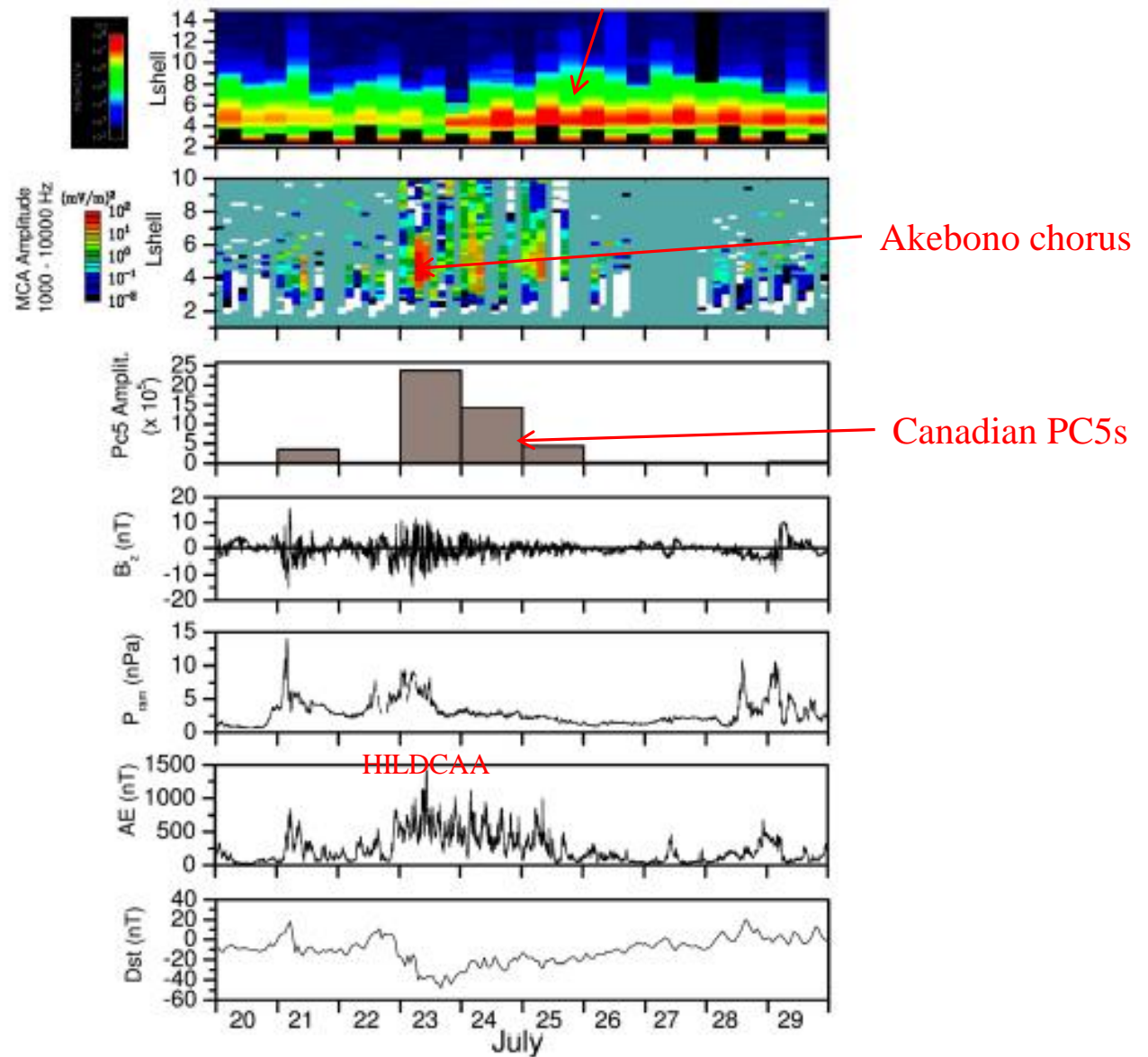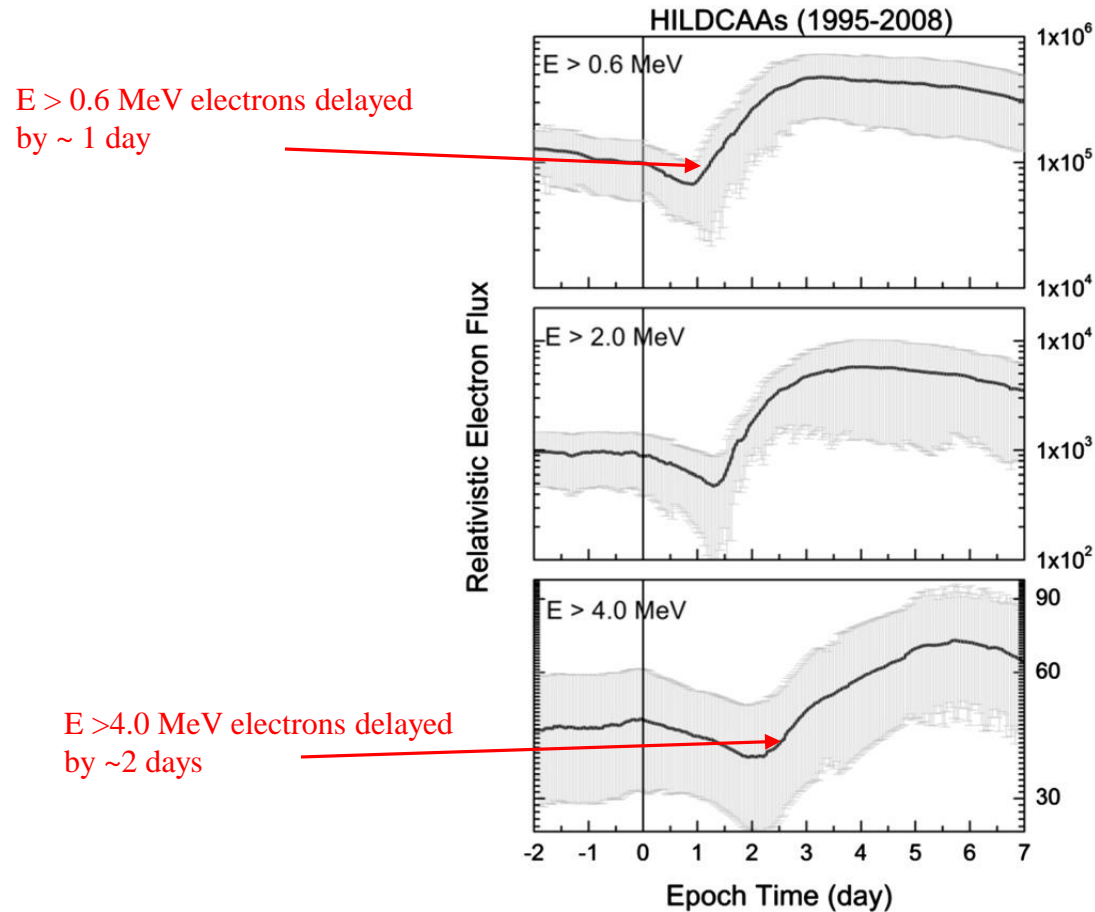
Chorus is now considered as the primary mechanism of ~100 keV electron acceleration to ~ MeV energies:

Inan et al.,JGR,1978; Horne and Thorne, GRL 1998, 2003; Summers et al., JGR 1998, 2007; Horne et al., JGR 2003a, GRL 2003b; Omura et al. JGR 2007; Thorne et al. JGR 2005, Nature 2013

Relativisitic E > 0.6, > 2.0 and >4.0 MeV Electron Acceleration at L = 6.6 during HILDCAAs

E > 0.6 MeV electrons delayed by ~ 1 day

E >4.0 MeV electrons delayed by ~2 days

HILDCAAs (1995-2008)

E > 0.6 MeV

E > 2.0 MeV

E > 4.0 MeV

Relativistic Electron Flux

Epoch Time (day)

With this new result, we can now "predict" when relativistic electrons will be accelerated, thus protecting Earth-orbiting satellites.

Hajra et al. ApJ 2015

Scenario

Magnetic reconnection associated with the Alfvén waves cause 10-100 keV electron injections in the midnight sector of the magnetosphere.

The 10-100 keV anisotropic electrons generate electromagnetic plasma waves called "chorus".

The chorus waves accelerate the ~100 keV electrons to ~MeV energies.

Final Comments

- How could ~1 to 2 hr period interplanetary Alfven waves lead to the generation of ~ kHz chorus and ~ MeV electrons?

- This is a multistep physical process and not at all obvious.

- Detailed analyses need to be done at each step and it is the combination of lots of separate efforts that lead to understanding.